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^{34}Cl via the ^{32}S(^{3}He,p) reaction*

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The structure of ^{34}Cl has been investigated with the reaction ^{32}S(^{3}He,p). Angular distributions were obtained for 29 levels below 5 MeV excitation. Extracted L values, combined with previous information, allow J^{π} assignments of 3^+ for states at 2181 and 2611 keV, negative parity for the $J = 4$ state at 3600 keV, 2^- for the level at 4514 keV, and 3^- (2^-) for states at 4416 and 4461 keV. Two new states are observed at excitation energies of 4693 and 4825 keV.

[NUCLEAR REACTIONS ^{32}S(^{3}He,p), E(^{3}He) = 18 MeV; measured $\sigma(E_p, \theta)$; gas H_2S target. ^{34}Cl deduced levels, L, J, π.]

I. INTRODUCTION

The spherical shell model is particularly successful for those nuclei which can be viewed as having an inert core and whose properties are basically determined by a few additional particles and (or) holes. The nucleus ^{34}Cl falls into this category. Its ground state may be viewed as consisting of a ^{32}S core—essentially the closed $d_{5/2}s_{1/2}$ shell—with a proton and a neutron in the $d_{3/2}$ shell coupled to $J^{\pi} = 0^+$. (The ground state of ^{32}S has indeed been shown to be a reasonably good closed core.)[1,2] In the ^{32}S(^{3}He,d)^{33}Cl and ^{32}S(d,p)^{33}S reactions,[1,2] the lowest $\frac{3}{2}^+$, $\frac{7}{2}^-$, and $\frac{3}{2}^-$ carry most of the appropriate stripping strength. The spectra of ^{34}Cl and ^{34}S have been used to obtain $(1d_{3/2})^2$ and $(1d_{3/2})(1f_{7/2})$ matrix elements.[3,4]

On the other hand, shell-model calculations[5] that give a good account of much data in this mass region produce a wave function for the ground state (g.s.) of ^{32}S that is only about 40% closed $(1d_{5/2})(2s_{1/2})$ core. The particle occupations in that work were $11.36d_{5/2}$, $3.10s_{1/2}$, and $1.54d_{3/2}$, to be compared with 12, 4, and 0, respectively, for a closed core.

Two-nucleon transfer on ^{32}S should provide a sensitive test of configuration mixing in the g.s. wave function, through the coherence properties of two-particle transfer amplitudes.

We have carried out two such experiments, ^{32}S(^{3}He,p)^{34}Cl at E(^{3}He) = 18 MeV, and ^{32}S(^{6}Li,α)^{34}Cl at E(^{6}Li) = 24 MeV. Here we report on our (^{3}He;p) results. The extracted L values are consistent with the spins and parities of the low-lying states,[7] permit a definite assignment of spin and parity for several of the higher states, and allow restrictions on J^{π} values for several other higher states. Two new states were observed at excitation energies of 4693.0 ± 3.4 and 4824.8 ± 2.4 keV.

II. EXPERIMENTAL PROCEDURE

The reaction ^{32}S(^{3}He,p)^{34}Cl has been studied using an 18 MeV ^{3}He beam from the University of Pennsylvania tandem accelerator. The target was H_2S gas flowing through a differentially pumped gas cell with no foil over its entrance channel.[6] The exhaust of the vacuum pumps was bubbled through a lead acetate solution to remove from it the H_2S component. After the run, the oil was changed in all affected vacuum pumps. The outgoing protons were detected on nuclear emulsions in a multiangle broad-range magnetic spectrograph. A spectrum obtained at 7.5° is shown in Fig. 1. The energy resolution was 22–25 keV. Angular distributions were obtained for 29 states up to 5 MeV excitation. The angular distributions are shown in Figs. 2 through 5. Excitation energies were obtained on the basis of spectrometer magnet calibration and the knowledge of the ground state Q value.[7] The results shown in Table I represent averages from the first eight angles for each of the excited states. All but two of these excitation energies lie within one standard deviation of the values in the compilation.[7]

III. ANALYSIS AND DISCUSSION

The experimental data were compared with results of a distorted-wave Born-approximation (DWBA) calculation using the two-particle transfer option of the code DWUCK.[8] Optical-model parameters are standard and are listed in Table II. The comparison of the experimental data and the corresponding theoretical curves is presented in

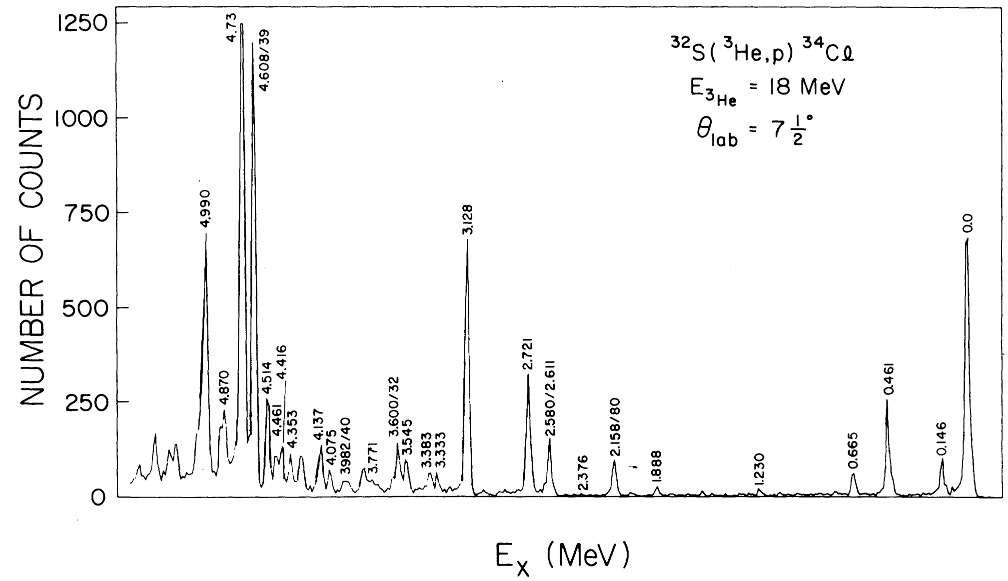

FIG. 1. Spectrum of protons from the $^{32}S(^{3}He,p)^{34}Cl$ reaction.

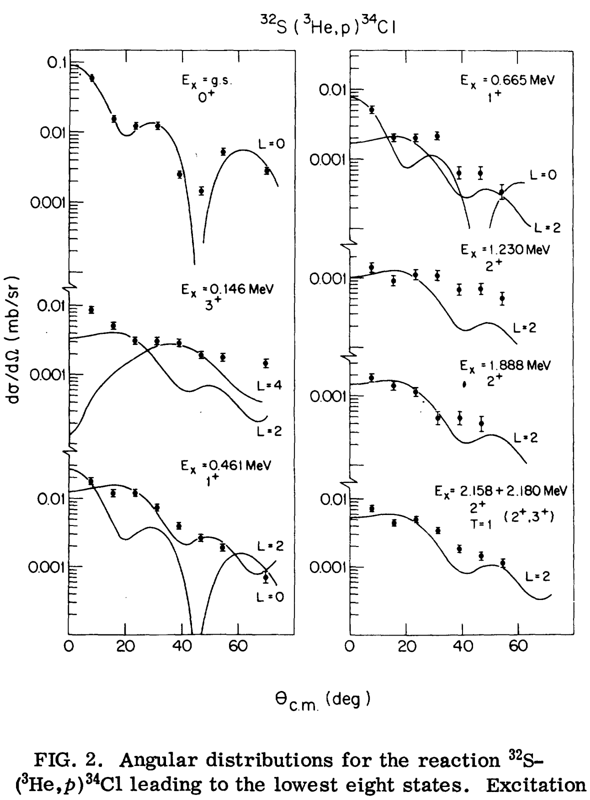

FIG. 2. Angular distributions for the reaction $^{32}S(^{3}He,p)^{34}Cl$ leading to the lowest eight states. Excitation energies are from Ref. 7. The curves are the results of pure-configuration DWBA calculations, and have been arbitrarily normalized to the data.

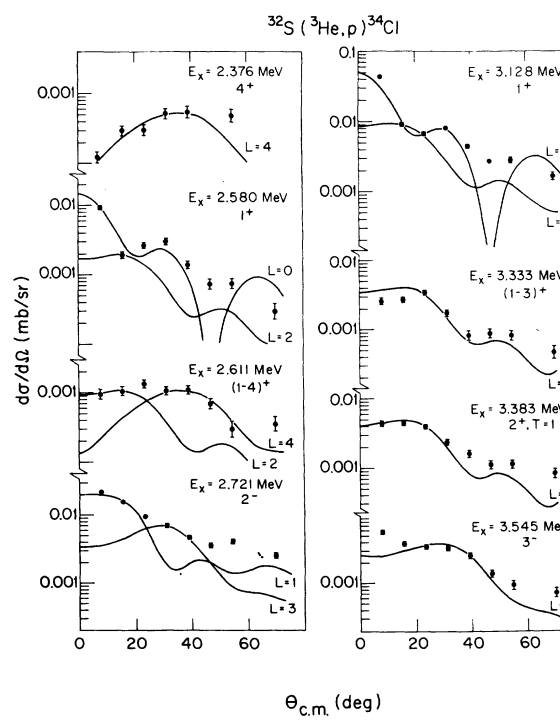

FIG. 3. Same as Fig. 2, but for states between 2.3 and 3.6 MeV excitation. Admixture of $L = 2+4$ for the 2611-keV state requires $J^{\pi} = 3^+$.

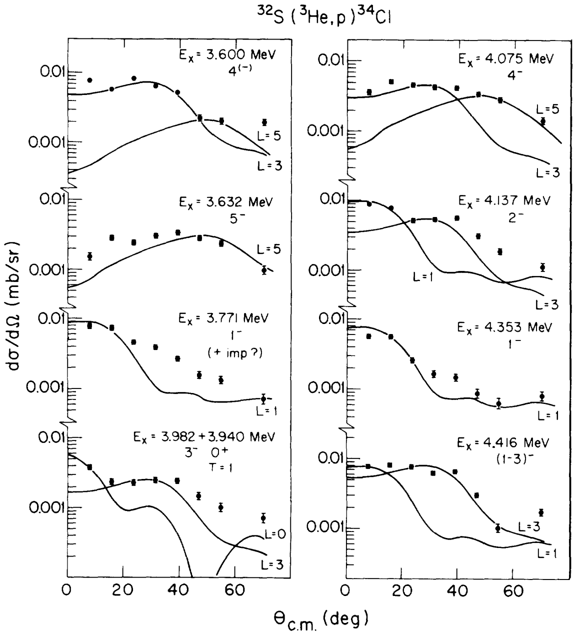

FIG. 4. Same as Fig. 2, but for states between 3.6 and 4.45 MeV excitation.

Figs. 2–5. All curves were calculated on the basis of pure configuration wave functions, since the shapes depend only very slightly on configuration. The L values of angular distributions in Fig. 2 are consistent with assignments[7] of 0^+ for the ground state, 1^+ for the 0.461- and the 0.665-MeV states, 2^+ for the 2.16-MeV state, and 3^+ for the 0.146-MeV state.

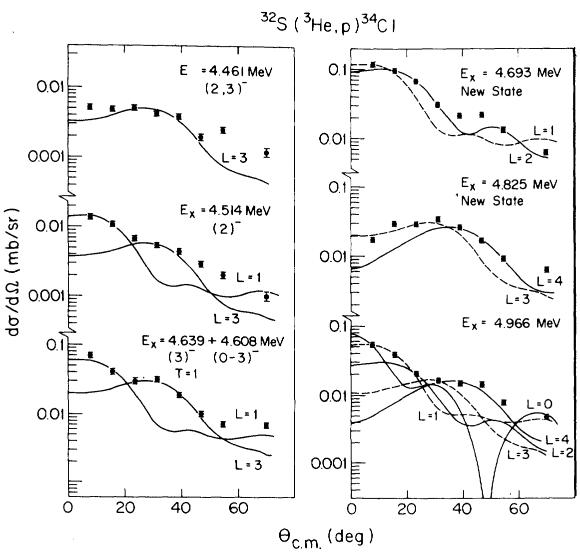

FIG. 5. Same as Fig. 2, but for states between 4.45 and 5.0 MeV excitation. Excitation energies for the three highest states are from the present work.

These states should contain most of the strength of the $(1d_{3/2})^2$ configuration, which gives rise to 0^+ and 2^+ states with $T=1$ and 1^+ and 3^+ states with $T=0$. The presence of two low-lying 1^+ levels indicates some configuration mixing. The shell-model calculations[5] and the ^{33}S(^{3}He,d)^{34}Cl reaction[3] both require that the second 1^+ contains most of the $(1d_{3/2})^2$ strength. Our results support this interpretation, since the lower 1^+ is dominated by $L=2$ while the second one contains an appreciable $L=0$ component. However, the relative strengths of the $L=2$ and $L=0$ contributions are only in rough agreement with theoretical wave functions.[9]

Previous investigations[7] have determined the parity of the 2.611-MeV state as positive, and have restricted its spin to values $J=1$, 2, 3, or 4. It can be seen in Fig. 3 that both $L=2$ and $L=4$ are required to fit the experimental data. This permits one to exclude $J=1$, 2, and 4 as possible spins, and leads to the assignment of $J^\pi=3^+$ for this state, if it is, indeed, a single state.

The first negative-parity state, a 2^- level, appears at an excitation energy of $E_x=2.721$ MeV. This state is thought to be dominated by the configuration $(1d_{3/2})(1f_{7/2})$. There should be four such pure two-particle states, with $J^\pi=2^-$, 3^-, 4^-, and 5^-. The 5^- state at 3.632 MeV is obviously of this configuration, as evidenced by its strong $l=3$ strength in ^{33}S(^{3}He,d)^{34}Cl.[3] The identification of the 3^- and 4^- members is less clear. Two 3^- states are known, at 3.545 and 3.982 MeV. In our data, both exhibit appreciable, and comparable, $L=3$ strength. In (^{3}He,d), the 3.982-MeV level has a large $l=3$ strength, but the 3.545 is assigned $l=1$. It appears, though, that the $l=1$ assignment depends on only one data point and that $l=3$ might also fit. In any event, our data suggest that these two 3^- levels share the $(1d_{3/2})(1f_{7/2})$ strength. In fact, $l=3$ for the 3.545-MeV level yields a summed proton stripping strength that is within 10% of the sum-rule limit for $[(1d_{3/2})(1f_{7/2})]_{3^-}$.

A state at 4.075 MeV has a 4^- assignment, and the 3.600-MeV state has $J=4$ with parity unknown. In our data, the 4.075-MeV level is populated with a mixture of $L=3$ and 5, consistent with a J^π of 4^-. The presence of $L=5$ requires an appreciable $(1d_{3/2})(1f_{7/2})$ component. The 3.600-MeV state appears to be populated via $L=3$—implying negative parity. Thus the 4^- strength is also apparently split.

We have calculated the (^{3}He,p) cross sections expected for the 2^-, 3^-, 4^-, and 5^- members of a pure $1d_{3/2}1f_{7/2}$ multiplet and compared them with our experimental cross sections for the above states. The ratios are given in Table III. Also listed there are the measured $l=3$ proton spectroscopic factors[3] divided by the theoretical spectro-

TABLE I. Results of the $^{32}S(^3He,p)^{34}S$ reaction.

Present work E_x (keV)	Literature E_x (keV)	J^π	L (dominant)	Remarks
0 ±2.5	0	$0^+, T=1$	0	
145.3 ±1.6	146±	3^+	2+4	
461.8 ±3.4	461±	1^+	2	
664.7 ±5.4	666	1^+	0	
1230.4 ±7.3	1230	2^+	(2?)	
1880.0 ±5.3	1888	2^+	2	
2163.0 ±8.7	2158	$2^+, T=1$	2	
	2181	$(2,3)^+$		3^+ assigned
2376.8 ±7.5	2376	4^+	(4)	Very weak
2583.0 ±4.1	2581	1^+	0	
2614.2 ±3.8	2611	$(1-4)^+$	(2) & (4)	3^+ assigned
2720.5 ±3.9	2722	2^-	1+3	
3127.0 ±2.7	3128	1^+	0	
3336.4 ±3.1	3333	$(1-3)^+$	2	2^+ preferred
3383.2 ±4.3	3383	$2^+, T=1$	2	
3548.4 ±5.2	3545	3^-	3	
3601.1 ±4.9	3600	$4^{(-)}$	(3) or (4)	Weak; neg. parity assigned
3635.2 ±4.8	3632	5^-	5	
3804 ±29	3771	1^-		Includes new state or unknown impurity
3982.6 ±7.2	3940 ±40	$0^+, T=1$	(0)+3	
	3982	3^-		
4076.5 ±5.8	4075	4^-	5(+3)	
4141.1 ±7.9	4137	2^-	1+3	
4354.5 ±2.0	4353	1^-	1	
4412.1 ±3.1	4416	$(1-3)^-$	3	$3^-(2^-)$ preferred
4455.8 ±4.0	4461	$(2,3)^-$	3	3^- preferred
4514.5 ±3.2	4514	$(2)^-$	1+3	2^- confirmed
4611.9 ±7.0	4608	$(0-3)^-$	1+3	
	4639	$(3)^-, T=1$		
4693.0 ±3.4			2 or 1+3	New state
4824.8 ±2.4			3 or 4	New state
4965.7 ±7.1	4990 ±30	$0^+, T=1$	(1 or 2)	At least a doublet

scopic factors for a pure $1d_{3/2}1f_{7/2}$ multiplet. The single-particle strengths are observed to fluctuate by about a factor of 2 if the lowest state of each J is considered. The $(^3He,p)$ strengths vary by about a factor of 4. The purest state appears from $(^3He,d)$[3] to be the 5^-. In $(^3He,p)$, its ratio is smallest. This is just what one would expect. Configuration mixing would reduce the proton strengths, but should increase the two-particle transfer strength through coherence for the lowest states of given J^π.

The previous tentative assignment[3] of negative parity and the restriction of angular momentum to values of $J=1$, 2, or 3 for the 4.416-MeV state can also be made more definite in view of the $L=3$ character of the corresponding angular distribution. Of the possible J values, $J=1$ is excluded by the presence of $L=3$. An $L=1$ admixture in the angular distribution cannot be completely ruled out, but if present it is very weak. Thus $J^\pi=3^-$ or perhaps 2^- is the most probable assignment for this state (Fig. 4).

Similarly, we would expect a contribution of $L=1$ to show up in the angular distribution of the state

TABLE II. Optical-model parameters used in analysis of $^{32}S(^3He,p)^{34}Cl$.

	V (MeV)	r_0 (fm)	a (fm)	W (MeV)	$W'=4W_D$ (MeV)	r_0' (fm)	a' (fm)	V_{so} (MeV)
^{3}He	170	1.14	0.723	20	0	1.60	0.80	0
p	60	1.13	0.57	0	34.2	1.13	0.50	5.5
bound state	···	1.26	0.60	···	···	···	···	$\lambda=25$

TABLE III. Comparison of one- and two-particle transfer strengths for low-lying negative-parity states.

E_x (MeV)	J^π	$\frac{S_p(\text{exp})^{a}}{S_p(\text{th})}$	$\frac{\sigma_{\text{exp}}}{\sigma_{\text{th}}}^{b}$
2720	2^-	0.91	114
4141	2^-	0.58	51
3548	3^-	0.63	66
3983	3^-	0.74	43
3601	4^-	···	130
4076	4^-	0.69	100
3635	5^-	1.19	30

[a] The experimental $l=3$ proton spectroscopic factors from Ref. 3 divided by the theoretical $l=3$ spectroscopic factor for a pure $1d_{3/2}1f_{7/2}$ state.

[b] Our measured (^{3}He,p) cross sections divided by the theoretical cross sections for a pure $1d_{3/2}1f_{7/2}$ state.

at 4.461 MeV—if its spin were $J=2$. Considering the absence of a forward rise and the $L=3$ feature of the corresponding angular distribution (Fig. 5), we prefer 3^- for the 4.461-MeV state.

For the 4.514-MeV state we definitively confirm the previous tentative assignment of $J^\pi = 2^-$ because $L=1$ and $L=3$ contributions both appear in the angular distribution.

These three states (those at 4.416, 4.461, and 4.514 MeV) were all populated with $l=1$ in (^{3}He,d) with no evidence for $l=3$—implying a dominant configuration of $(1d_{3/2})(2p_{3/2})$.

Additional negative-parity states at 3.771, 4.137, 4.353, 4.608, and 4.639 MeV, from our data, and from (^{3}He, d), appear to contain large components of $(1d_{3/2})(2p_{3/2})$, though the 4.137-MeV 2^- state also has an admixture of $(1d_{3/2})(1f_{7/2})$.

States of 4.693 and 4.825 MeV are new states. They are quite strongly excited in the (^{3}He,p) reaction. The 4.693-MeV level is populated with either $L=2$ or a mixture of $L=1$ and 3, implying $J^\pi = (1,2,3)^+$ or 2^-. The 4.825-MeV state appears to require $L=3$ or 4.

The angular distribution for the state we observe at $E_x = 4.966$ MeV is compared in the figure with theoretical curves for $L=0,1,2,3,4$. It cannot be fitted with any single L value. Since a 0^+, $T=1$ state is known to exist at 4.99 ± 0.03 MeV, our level is at least a doublet.

A number of low lying positive-parity states cannot be accounted for by the simple shell model. However, an extended shell-model calculation involving ^{32}S core excitation does account for many of these states. In fact, for all the positive-parity states below 3.5 MeV, a one-to-one correspondence can be made with the shell-model states,[5] as depicted in Fig. 6. Most of these states are weak in (^{3}He,p) as expected for core-excited states. The model has some additional states which may imply that some of the known states are actually unresolved doublets. The 2.181-MeV $(2,3)^+$ state is unresolved in the present work from the 2^+, $T=1$ state at 2.158 MeV. The combined angular distribution appears to contain an $L=4$ component, implying 3^+ for the 2.18-MeV level. A 3^+ assignment fits in with the shell model, which has 3^+ states at 1.19 and 1.83 MeV, and no other 2^+, $T=0$ states below 2.54 MeV.

The state at 2.61 MeV, previously known to be $(1-4)^+$, is also assigned 3^+ in the present work. This state is presumably to be identified with one of the 3^+ model states at 1.83 and 2.25 MeV. In any case, one theoretical 3^+ state is missing.

The 3.33-MeV state has been previously assigned $(1-3)^+$. Its angular distribution in the present work implies $J^\pi = 2^+$. We thus tentatively identify it with the 2^+ model state at 2.54 MeV.

States in the model spectrum remaining to be identified are two 4^+, two 5^+, one 2^+, and one 3^+ state. It may be that two of them are the two new

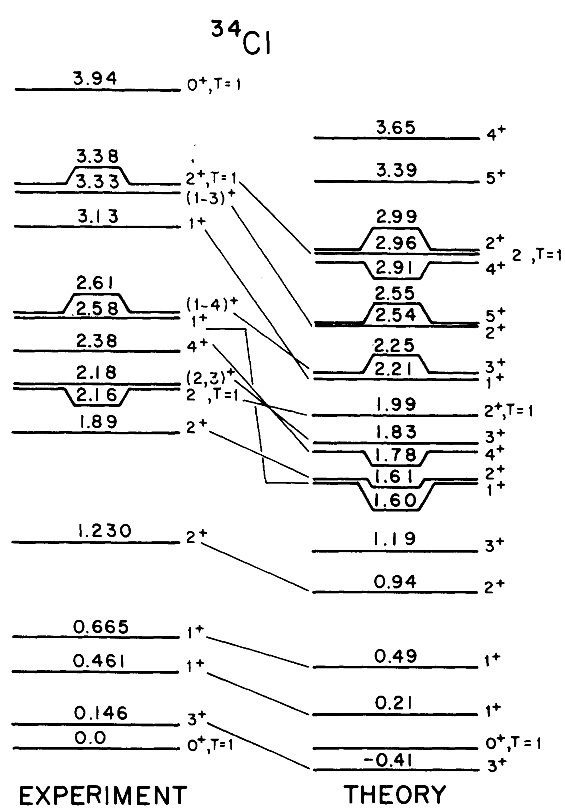

FIG. 6. Comparison of experimental (Ref. 7) and theoretical (Ref. 5) energies and J^π values for low-lying positive-parity states in ^{34}Cl. The present work assigns $J^\pi = 3^+$ to the states at 2.18 and 2.61 MeV, and suggests 2^+ for the 3.33-MeV state.

states we observe at 4.69 and 4.83 MeV.

The 1^+ state at 3.13 MeV is much stronger than one would expect within the *sd*-shell model space and hence it probably contains appreciable components with two nucleons in the *fp* shell. The two new states at 4.69 and 4.83 MeV are also so strong that they must contain large terms with one or two particles in the *fp* shell.

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