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^{34}S by the ^{32}S$(t,p)^{34}$S reaction*

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The ^{32}S$(t,p)^{34}$S reaction was studied at a bombarding energy of E_t = 10 MeV. The outgoing protons were analyzed in a multiangle magnetic spectrograph. Levels in ^{34}S below E_x = 8.50 MeV were identified and angular distributions were extracted for 30 groups. These angular distributions were analyzed using distorted-wave techniques. Results are compared to recent shell-model calculations.

[NUCLEAR REACTIONS ^{32}S(t,p), E=10 MeV; measured $\sigma(E_p,\theta)$. Deduced ^{34}S levels, J, π, configurations. DWBA analysis.]

I. INTRODUCTION

Recent experimental evidence has shown that ^{32}S is a reasonably good closed-shell nucleus. In particular, a study[1] of the ^{32}S$(d,p)^{33}$S reaction at 18 MeV demonstrated that the ground state of ^{33}S accounted for a preponderance of the $1d_{3/2}$ sum-rule stripping strength, and the 2.94-MeV level for most of the $1f_{7/2}$ strength. Little $2s_{1/2}$ strength and negligible $1d_{5/2}$ strength were observed. By means of the ^{32}S$(^3$He$,d)^{33}$Cl reaction, a similar result was obtained[2] for the mirror nucleus ^{33}Cl. Thus, the first $\frac{3}{2}^+$ and $\frac{7}{2}^-$ states in these mass-33 nuclei appear to be good single-particle states.

If the mass-33 nuclei exhibit single-particle spectra, it follows that the structure of the mass-34 nuclei ^{34}Cl and ^{34}S should be simple and easily interpreted as two nucleons outside of a ^{32}S core. Working on this hypothesis, investigations of the mass-34 nuclei were undertaken; studies of the reactions ^{33}S$(^3$He$,d)^{34}$Cl [3] and ^{33}S$(d,p)^{34}$S [4] revealed that the mass-34 nuclei were, in fact, convenient sources for obtaining the $(d_{3/2})^2$ and $(d_{3/2}f_{7/2})$ matrix elements of the two-body interaction. This initial success suggested that additional study of the mass-34 nuclei might be profitable.

The present analysis of the ^{32}S$(t,p)^{34}$S reaction was undertaken for two reasons. First, since the target ^{32}S has a 0^+ ground state, the assignment of an L value by means of distorted-wave (DW) analysis, leads to an unambiguous J^π assignment. Secondly, this reaction was likely to reveal information about the $(f_{7/2})^2$ component of the two-body interaction.

For convenience in the later discussion, an energy level diagram for ^{34}S is presented in Fig. 1. The spin and parity assignments include the results of the present work.

II. EXPERIMENTAL PROCEDURE AND RESULTS

The Aldermaston tandem Van de Graaff accelerator supplied the 10-MeV triton beam used to induce the ^{32}S$(t,p)^{34}$S reaction. Because elemental sulfur is extremely volatile, either a low intensity beam current must be used or the target must be composed of a suitable stable compound. In the present experiment the latter alternative was chosen; an antimony trisulfide target was employed. Protons resulting from the (t,p) reaction were analyzed in a multiangle magnetic spectrograph[5] and recorded in nuclear emulsion plates. Polythene absorbers of sufficient thickness to stop charged particles other than protons were placed in the focal plane of the spectrograph.

A typical spectrum, recorded in the spectrograph, is shown in Fig. 2. The groups resulting from the (t,p) reaction on ^{32}S are denoted by numbers, which, in Table I, are identified with the excitation energies measured in the present experiment and with excitation energies from the literature.[4,6–10] In addition to the groups resulting from the ^{32}S$(t,p)^{34}$S reaction, impurity groups resulting from antimony in the target are also identified. The angular distributions which were extracted are shown in Figs. 3–10. The solid and broken lines in the figures are the results of DW calculations, which will be explained in the next section.

III. ANALYSIS

Table II gives the optical-model parameters[11,12] used for the analysis of the ^{32}S$(t,p)^{34}$S reaction. Since only a limited amount of triton elastic scattering data is available, parameters obtained for ^{3}He were employed for the entrance channel. Considerable effort was devoted to attempting to im-

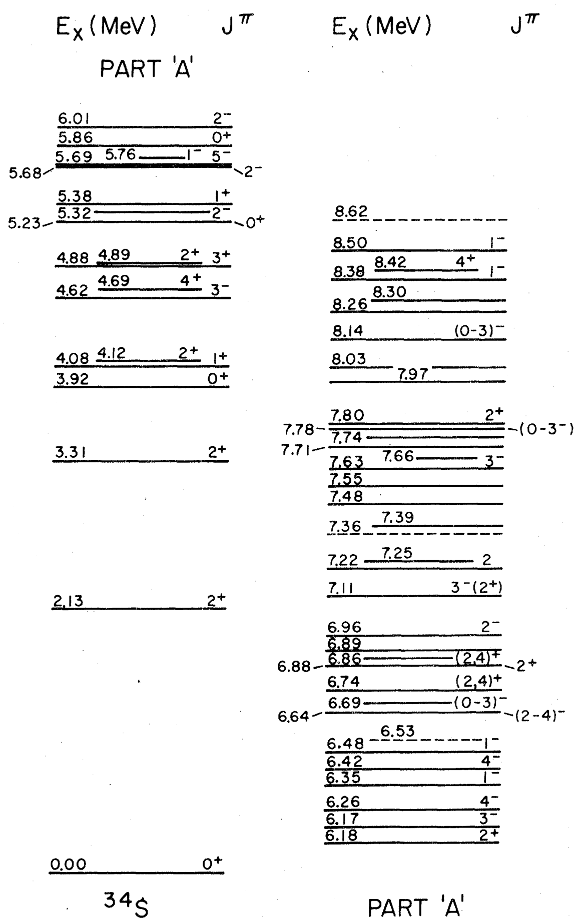

FIG. 1. Energy level diagram for ^{34}S. Spin parity assignments include those of the present work.

prove the fits by varying the triton parameters, but little improvement was found. The two sets of triton parameters which were used (given in Table II) differ only in the imaginary radius r_0'. The distorted-wave calculations were performed by utilizing the two-particle-transfer option in the code DWUCK.[13]

Since no two-particle transfer amplitudes from shell-model calculations were available for this reaction, pure configurations were assumed for the bound-state form factors. The dependence of shapes on assumed configuration is discussed later. Relative normalizations of the experimental to theoretical cross sections are given in Table III. Since only relative cross sections were measured, and since the absolute normalizing factor for a (t,p) DW calculation is not known, the normalization for the ground state has been chosen equal to 100. For most of the strongly populated levels, Table III gives normalizations obtained for several possible configurations. No strict criterion has been applied for the choice of configuration used.

Table IV gives a summary of available spectroscopic information for the levels in ^{34}S for which angular distributions were extracted. In Table IV the levels are identified by excitation energy in the first column; L values from the present study are given in the second column; l_n values from the $^{33}S(d,p)^{34}S$ reaction and l_p values from $^{35}Cl(d,{}^3He)^{34}S$ are given in the third and fourth columns; the fifth, sixth, and seventh columns of the table give information from γ-decay studies; the eighth column gives the best J^π assignment, in the opinion of the authors.

IV. DISCUSSION

In this section we shall discuss individually the states for which $^{32}S(t,p)^{34}S$ angular distributions have been extracted.

A. $L=0$ transitions: Levels at 0.00, 3.92, 5.22, 5.86, and 8.02 MeV in excitation

Shown in Fig. 3 are the five angular distributions which are characteristic of $L=0$ transfer. Thus these five levels are 0^+ states.

The ground state of ^{34}S is populated by an $l_p=2$ transition in $^{35}Cl(d,{}^3He)^{34}S$ [14,15] and by $l_n=2$ in the $^{33}S(d,p)^{34}S$ reaction.[4,16] It is primarily of a $(d_{3/2})^2$ configuration. The large strength observed for the ground state, as evidenced by the large relative normalization in Table III, is expected and arises from coherent admixtures of other configurations.

The state at 3.92 MeV excitation has also been observed in the reactions $^{37}Cl(p,\alpha)^{34}S$,[17] $^{33}S(d,p)$-^{34}S,[10] $^{34}S(p,p')^{34}S$,[9] and $^{31}P(\alpha,p)^{34}S$.[7,8,18,19] Its γ decay to the 2.13-MeV 2^+ level has been observed[7,8,19] and a lifetime of 1.60 ± 0.13 ps[8] was measured by the Doppler shift attenuation method (DSAM). The angular distribution of this level has been fitted in Fig. 3 with the assumption of an $(f_{7/2})^2$ configuration; Table III gives relative normalizations for $(d_{3/2})^2$ and $(s_{1/2})^2$ configurations also. This is the weakest of the $L=0$ transitions observed in the present investigation and is most likely a core-excited state.

The 5.22-MeV level has been observed also in the $^{34}S(p,p')^{34}S$ [9] and $^{31}P(\alpha,p)^{34}S$ [19] reactions. The γ decay to the 4.08-MeV 1^+ state has been observed[19] and angular-correlation measurements are consistent with the 0^+ assignment obtained from the $^{32}S(t,p)^{34}S$ reaction. The angular distribution has been fitted with the DW curve from an $(f_{7/2})^2$ configuration in Fig. 3; relative normalizations for $(d_{3/2})^2$ and $(p_{3/2})^2$ configurations are also given in Table III. Like the 3.92-MeV level, this level is only weakly populated in $^{32}S(t,p)$-^{34}S and may also be a core-excited state.

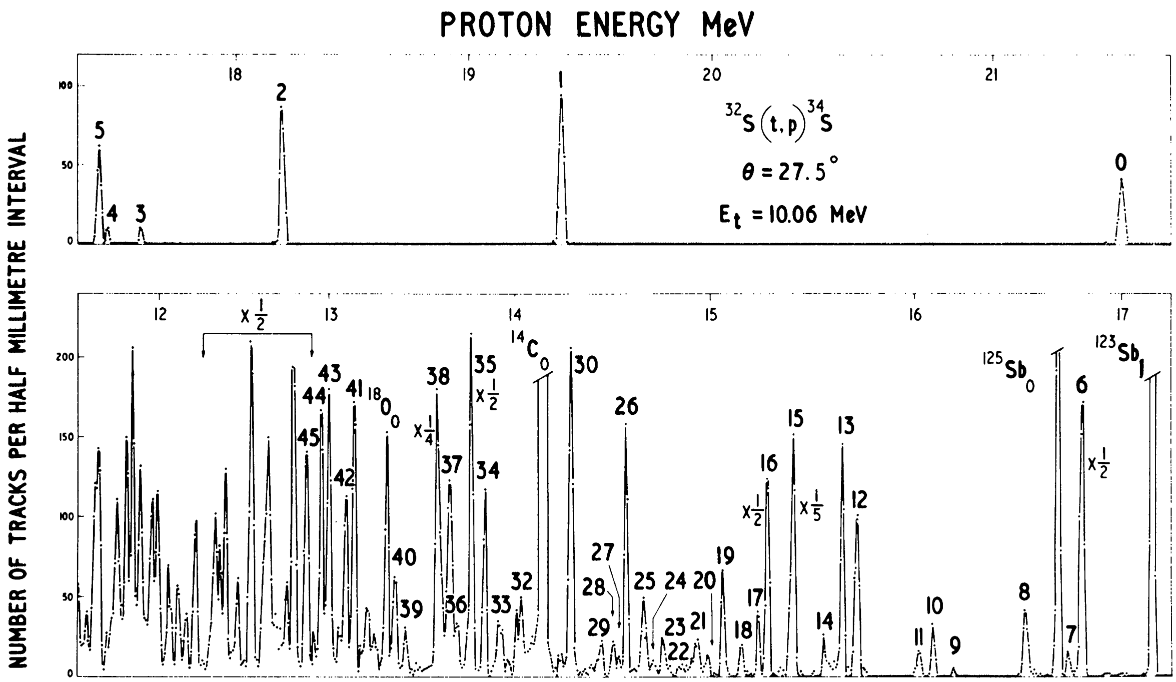

FIG. 2. Typical spectrum of protons recorded in the spectrograph. States in ^{34}S are numbered in accordance with excitation energies given in Table I. Impurity groups from the (t,p) reaction on carbon, oxygen, and antimony in the target are also observed.

The 5.86-MeV state is also observed in the $^{34}S(p,p')^{34}S$ reaction.[9] It is the second strongest $L=0$ transition observed in the $^{32}S(t,p)^{34}S$ reaction and probably is primarily of an $(f_{7/2})^2$ configuration.[20] The possible observation of configuration dependence in the angular distribution of this state is discussed in Sec. IV J.

The final $L=0$ transition observed in the present

TABLE I. Energy levels of ^{34}S observed in the $^{32}S(t,p)^{34}S$ reaction.

Group No.	E_x (MeV ± keV) Present work	Literature	Group No.	E_x (MeV ± keV) Present work	Literature	Group No.	E_x (MeV ± keV) Present work	Literature
0	0.000	0.000	16	6.128 ± 14	6.118 ± 14 [a]	30	7.245 ± 15	7.248 ± 18 [a]
1	2.128 ± 10	2.127 52 ± 0.20 [b]	17	6.179 ± 14	6.174 ± 8 [c]	31	7.388 ± 15	(7.360 ± 18) [a]
2	3.308 ± 11	3.303 1 ± 0.4 [d]	18	6.256 ± 14	6.256 ± 8 [c]	32	7.472 ± 15	7.479 ± 14 [a]
3	3.915 ± 12	3.915 1 ± 0.9 [e]	19	6.349 ± 14	6.346 ± 8 [c]	33	7.547 ± 16	7.549 ± 14 [a]
4	4.085 ± 12	4.071 8 ± 1.0 [d]	20	6.423 ± 14	6.422 ± 8 [c]	34	7.621 ± 16	7.631 ± 10 [f]
5	4.121 ± 12	4.114 2 ± 0.8 [d]	21	6.488 ± 14	6.483 ± 8 [c]	35	7.714 ± 16	
6	4.623 ± 13	4.622 2 ± 0.6 [d]	22	6.535 ± 15		36	7.739 ± 16	7.732 ± 11 [c]
7	4.690 ± 13	4.687 5 ± 0.6 [d]	23	6.639 ± 15	6.644 ± 9 [c]	37	7.801 ± 16	
8	4.888 ± 13	4.875 2 ± 0.6 [d]	23a	6.69 ± 15	6.690 ± 9 [c]	38	7.971 ± 16	
		4.889 6 ± 4.0 [d]	24	6.743 ± 15	6.738 ± 25 [a]	39	8.025 ± 16	
9	5.225 ± 13	5.228 ± 14 [a]	25	6.828 ± 15	6.832 ± 9 [c]	40	8.255 ± 16	
10	5.320 ± 13	5.318 ± 2 [c]	26	6.869 ± 15	6.860 ± 14 [a]	41	8.293 ± 16	8.299 ± 14 [f]
11	5.380 ± 13	5.384 ± 6 [c]	27	6.898 ± 15	6.888 ± 14 [c]	42	8.383 ± 16	
12	5.679 ± 14	5.683 ± 7 [c]	28	6.956 ± 15	6.959 ± 10 [f]	43	8.418 ± 16	
		5.694 ± 7 [c]	29	7.112 ± 15	7.112 ± 10 [f]	44	8.496 ± 16	
13	5.759 ± 14	5.758 ± 7 [c]						
14	5.859 ± 14	5.848 ± 18 [a]						
15	6.008 ± 14	5.995 ± 18 [a]						

[a] Reference 9.
[b] Reference 6.
[c] Reference 4.
[d] Reference 7.
[e] Reference 8.
[f] Reference 10.

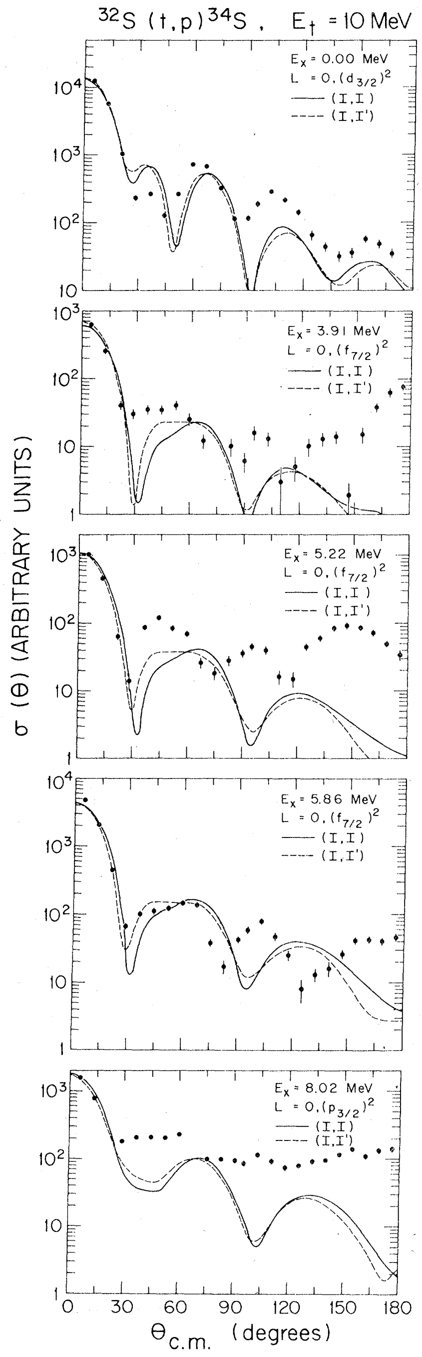

FIG. 3. Angular distributions for the levels populated by $L=0$ transitions. Solid and broken lines are DW calculations made with two parameter sets.

experiment is that to the 8.02-MeV level. This level may have a significant $(p_{3/2})^2$ component, but it is too weak in the (t,p) reaction to have a major fraction of the $(p_{3/2})^2$ strength.

B. $L=2$ transitions I: States at 2.13, 3.31, 4.12, and 4.89 MeV in excitation

Eight states possess angular distributions that are fitted with $L=2$ DW calculations in Fig. 4. They will be discussed in this and the following section. Most of these distributions have characteristic $L=2$ shapes, thus fixing the spin and parity assignments of the corresponding levels as 2^+. The $L=2$ fits to the angular distributions of the levels at 3.31 and 4.89 MeV are inferior to the others but these states have existing 2^+ assignments from other studies of ^{34}S. Other possible 2^+ states at 7.11 and 8.25 MeV will be discussed in Sec. IV H.

The state at 2.13 MeV is populated by an $l_p=0$ transition in the $^{35}Cl(d,{}^3He)^{34}S$ reaction[14,15] and by $l_n=0+2$ in $^{33}S(d,p)^{34}S$.[4,16] The decay of this state to the ground state has been observed,[7,8,18,19,21-23] and a lifetime of 400 ± 32 ps has been measured.[18] Angular correlation measurements assign $J=2$ to this level.[7] The first excited state of ^{34}S has also been observed in the $^{35}Cl(p,\alpha)^{34}S$[17] and the $^{34}S(p,p')^{34}S$[9] reactions. In Fig. 4, the $L=2$ DW calculation fits the angular distribution of this state quite well. Relative normalizations for both $(d_{3/2})^2$ and $(d_{3/2}s_{1/2})$ configurations are given in Table III.

The second-excited state at 3.31 MeV is also populated by an $l_p=0$ angular distribution in the $^{35}Cl(d,{}^3He)^{34}S$ reaction[14,15] and by $l_n=0+2$ in $^{33}S(d,p)^{34}S$.[4,16] Decays to both the ground state and the first-excited state have been observed.[7,8,18,19,21-23] Angular-correlation measurements have assigned $J=2$ for this level,[7,19] and the measured lifetime is 175 ± 25 fs.[18] The 3.31-MeV level has also been observed in the $^{37}Cl(p,\alpha)^{34}S$[17] and the $^{34}S(p,p')^{34}S$[9] reactions. In Fig. 4 this has been identified as $L=(2)$, because of the 2^+ assignment made by earlier studies. It will be noticed, however, that the DW calculation does not fit the angular distribution well. A $(d_{3/2}s_{1/2})$ configuration has been chosen in Fig. 4 since this level exhibits a larger $l_n=0$ component in the $^{33}S(d,p)^{34}S$ reaction than does the 2.13-MeV level. However, the relative normalization for an assumed $(d_{3/2})^2$ configuration is also given in Table III.

The $^{33}S(d,p)^{34}S$ reaction populates the state at 4.12 MeV with an admixed $l_n=0+2$ transition.[4,16] This level decays to the 0^+ ground state and to the 2^+ level at 2.13 MeV[7,8,18,19]; angular-correlation measurements assign $J=2$ to it.[19] The lifetime measured by DSAM is 110 ± 10 fs.[18] The angular distribution of this level (shown in Fig. 4) exhibits a characteristic $L=2$ shape. A $(d_{3/2})^2$ configuration has been assumed in Fig. 4 but relative normalizations for $(d_{3/2}s_{1/2})$ and $(f_{7/2})^2$ configurations

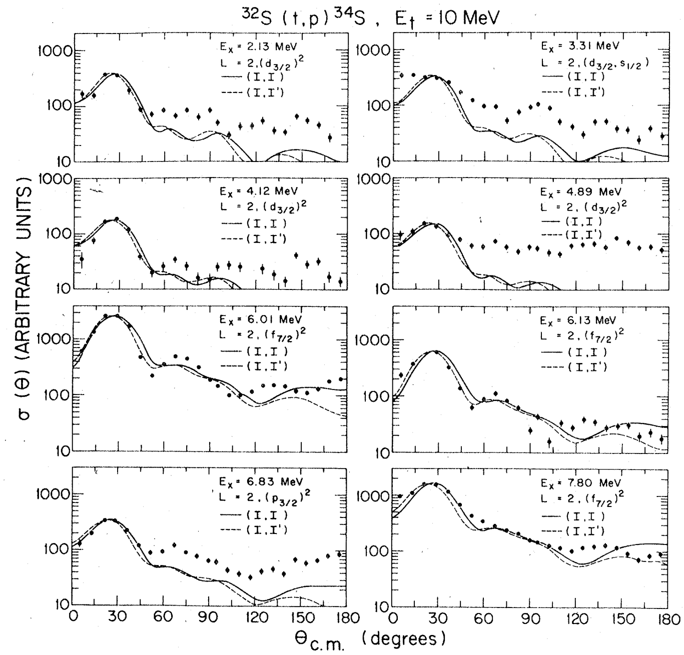

FIG. 4. Angular distribution for the levels populated by $L = 2$ transitions. Solid and broken lines are DW calculations made with two parameter sets.

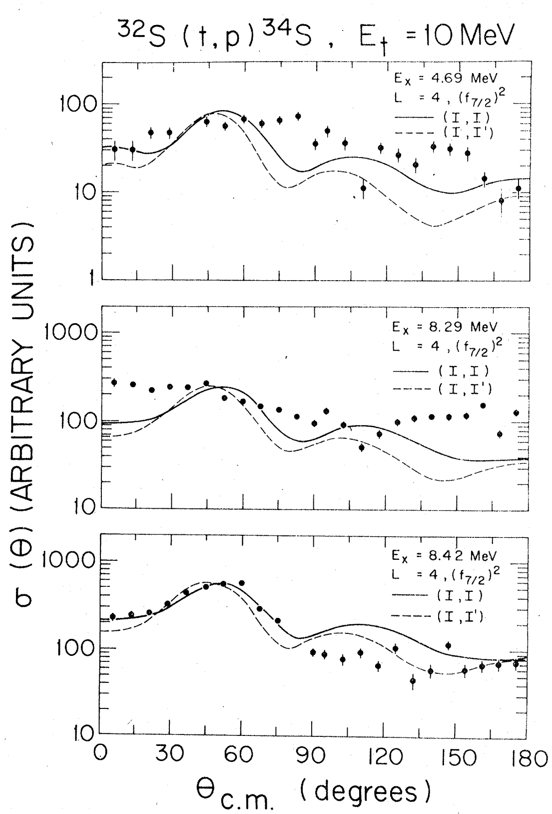

FIG. 5. Angular distributions for the levels populated by $L = 4$ transitions. Solid and broken lines are DW calculations made with two parameter sets.

are also given in Table III.

The group identified in the present work as 4.89 MeV is a doublet. This group has also been observed (but not resolved) in the $^{35}Cl(d, {}^3He)^{34}S$ reaction where an $l_p = 2$ transition is observed[14,15] and in the $^{37}Cl(p,\alpha)^{34}S$ [17] and the $^{34}S(p,p')^{34}S$ [9] reactions. The first member of the doublet has been observed to decay to the 2^+ levels at 2.13 and 3.31 MeV[7,8,19]; angular-correlation measurements yield $J = 3$ [19] and the measured lifetime is 57 ± 22 fs[18]; this level has been assigned spin and parity 3^+. The second member of the doublet has been observed to decay to the 0^+ ground state and to the 2^+ level at 3.31 MeV[7,8,19]; angular-correlation measurements assign $J = 2$ to this level[7,19] and the lifetime is 52 ± 14 fs[18]; this level has been assigned spin and parity 2^+. The $^{32}S(t,p)^{34}S$ angular distribution populating this group is shown in Fig. 4. It is compared with an $L = 2$ curve primarily because of the existing 2^+ assignment for the second member of the doublet; the unnatural parity of the first member of the doublet implies that that level should be weak in this reaction. A slight indication of the characteristic first maximum of an $L = 2$ distribution is observed. Relative normalizations obtained for assumptions of both $(d_{3/2})^2$ and $(f_{7/2})^2$ configurations are given in Table III. However, it should be pointed out that the angular distribution of this level is nearly symmetric about 90° and almost isotropic. Also, the total cross section, compared with that of the 1^+ level at 4.08

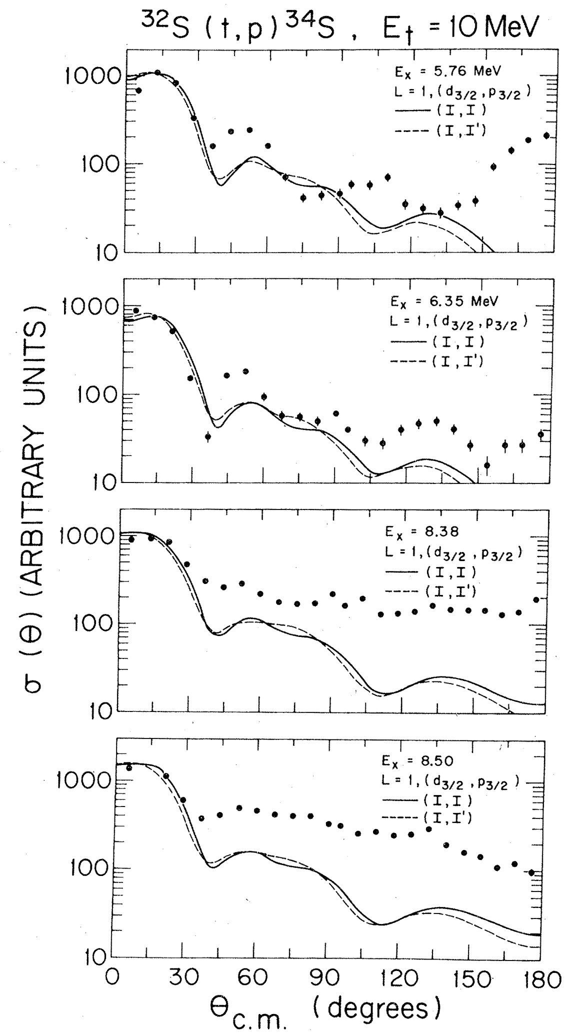

FIG. 6. Angular distributions for the levels populated by $L=1$ transitions. Solid and broken lines are DW calculations made with two parameter sets.

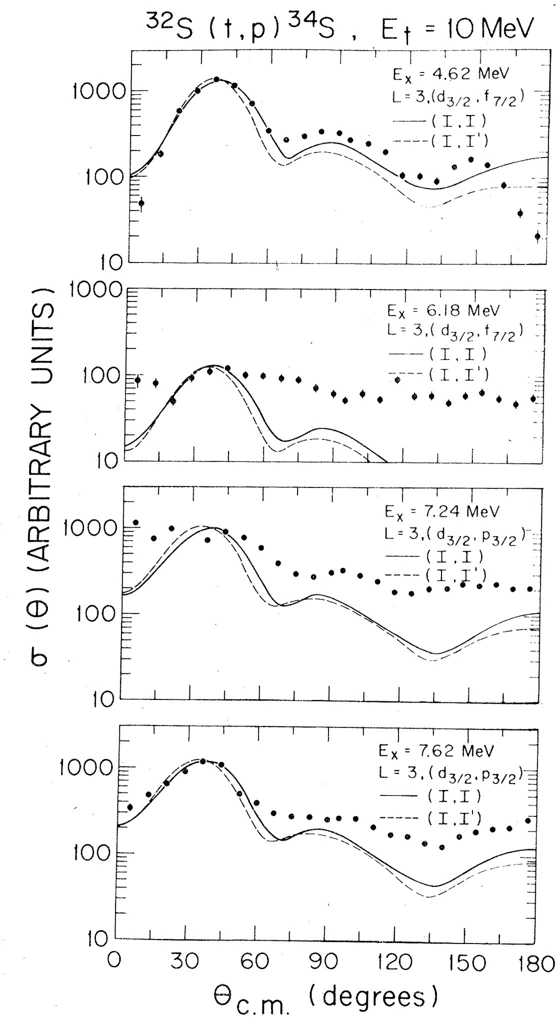

FIG. 7. Angular distributions for the levels populated by $L=3$ transitions. Solid and broken lines are DW calculations made with two parameter sets.

MeV (which will be discussed later) is consistent with a compound nucleus process populating both states of this doublet.

C. $L=2$ transitions II: States at 6.01, 6.13, 6.83, and 7.80 MeV

The state at 6.01 MeV decays to the 0^+ ground state, the 2^+ level at 2.13 MeV, and the 1^+ level at 4.08 MeV.[24] Angular-correlation measurements[24] indicate $J=2$. This level has also been observed in the $^{34}S(p,p')^{34}S$ reaction.[9] An $L=2$ calculation describes the shape of the angular distribution, shown in Fig. 4, well; in fact, this is the strongest $L=2$ distribution observed. Hence the state has $J^\pi=2^+$. Relative normalizations for both $(f_{7/2})^2$ and $(p_{3/2})^2$ configurations are given in Table III.

The 6.13-MeV state decays to the 2^+ states at 2.13 and 3.31 MeV.[24] Angular-correlation measurements have limited the spin of this level to (1, 2).[24] The 6.13-MeV level has also been observed in the $^{34}S(p,p')^{34}S$ [9] and $^{33}S(d,p)^{34}S$ [4] reactions. The angular distribution, shown in Fig. 4, possesses an $L=2$ shape, thus implying a spin and parity assignment of 2^+ for the 6.13-MeV level.

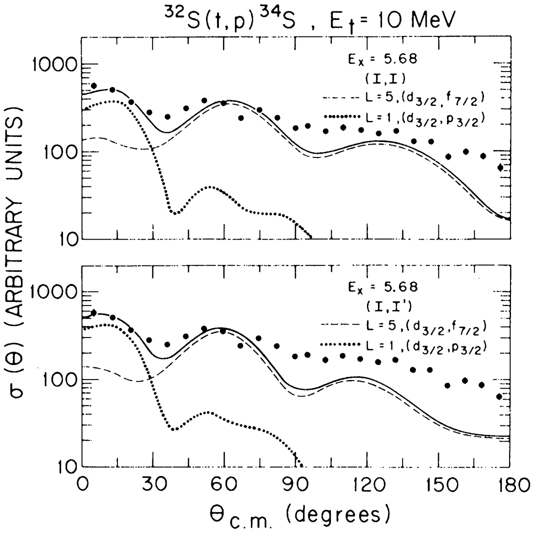

FIG. 8. Angular distribution for the doublet at 5.68 MeV (not resolved in the present experiment). Broken lines indicate DW calculations for $L=1$ and $L=5$. The solid line indicates the sum of these two L values.

The level at 6.83 MeV is populated by an $l_p=0$ transition in ^{35}Cl$(d,{}^3$He$)^{34}$S [14] and by $l_n=0$ in ^{33}S$(d,p)^{34}$S.[4] This level decays to the 0^+ ground state, the 2^+ level at 4.12 MeV, and the 3^- state at 4.62 MeV.[24] The angular distribution observed in Fig. 4 possesses the characteristic $L=2$ shape, implying a spin and parity of 2^+ for the 6.83-MeV level.

In Fig. 4, the angular distribution of the 7.80-MeV level exhibits the characteristic $L=2$ shape and is the second strongest 2^+ state observed. It has been pointed out[20] that this level is probably the principal 2^+ component of the $(f_{7/2})^2$ configuration.

D. $L=4$ transitions: Levels at 4.69, 8.29, and 8.42 MeV

Figure 5 displays the angular distributions for three levels which we have attempted to fit with $L=4$ DW calculations. Of these, only the level at 8.42 MeV demonstrates a definite $L=4$ shape.

The state at 4.69 MeV is populated by an $l_p=2$ distribution in the ^{35}Cl$(d,{}^3$He$)^{34}$S reaction.[14,15] It has also been observed in ^{37}Cl$(p,\alpha)^{34}$S,[17] ^{33}S(d,p)-^{34}S,[10] and ^{34}S$(p,p')^{34}$S.[9] The 4.69-MeV state decays to the 2^+ level at 2.13 MeV.[7,8,18,19,25] Angular-correlation measurements yield $J=4$ for this state[19]; the lifetime is 131 ± 13 fs.[18] Since the foregoing information indicates that this is a 4^+ level, the angular distribution shown in Fig. 5 has been fitted with an $L=4$ DW calculation. The distribution does not, however, exhibit the shape expected and is, in fact, weak and nearly symmetric about 90°, suggesting that this level may be populated by a compound mechanism.

The state at 8.29 MeV has been identified previously in the ^{33}S$(d,p)^{34}$S reaction.[10] The angular distribution of this level, shown in Fig. 5, does not exhibit a recognizable shape. The $L=4$ distribution shown produces the best fit to the data but this is not enough evidence to make a definite assignment. The angular distribution is, in fact, somewhat similar to that observed for the 3.31-MeV 2^+ state.

The 8.42-MeV level exhibits the strongest $L=4$ angular distribution (shown in Fig. 5) observed in

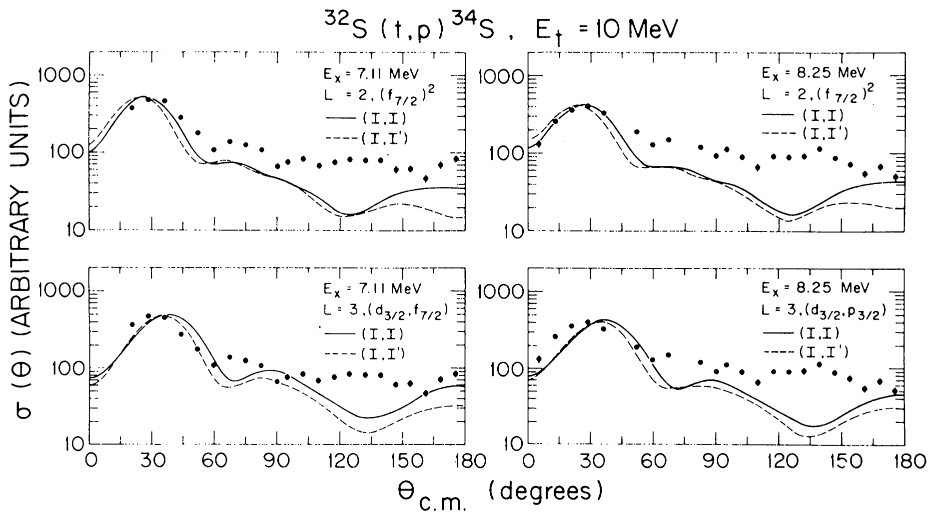

FIG. 9. Angular distributions for the levels at 7.11 and 8.25 MeV. Distributions are shown fitted with both $L=2$ and $L=3$ DW calculations for two parameter sets—solid and broken lines.

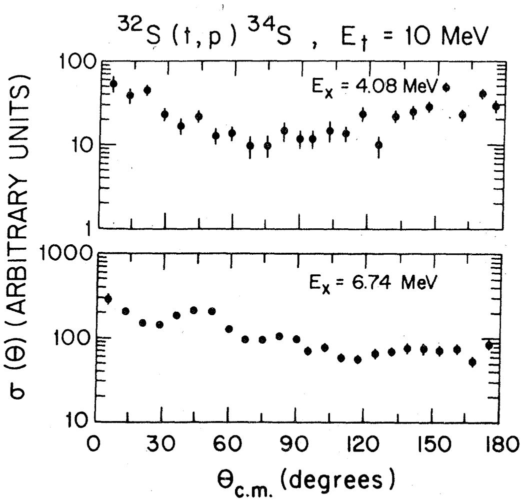

FIG. 10. Angular distributions of states which could not be adequately fitted with DW calculations.

the present experiment. In fact, this is the only level for which a 4^+ assignment can be made on the basis of the present data. This level has been suggested[20] to be the 4^+ member of the $(f_{7/2})^2$ multiplet.

E. $L=1$ transitions: States at 5.76, 6.35, 8.38, and 8.50 MeV

The angular distributions of the four levels shown in Fig. 6 exhibit characteristic $L=1$ shapes, implying that these are 1^- levels.

The level at 5.76 MeV is populated by an $l_n=1$ distribution in the ^{33}S$(d,p)^{34}$S reaction[4,16] and has also been identified in the ^{34}S$(p,p')^{34}$S reaction.[9] The angular distribution of the 5.76-MeV level is characterized by an $L=1$ shape and this is sufficient to assign $J^\pi=1^-$ to this level.

The level at 6.35 MeV is populated by an $l_n=1$ transition in the ^{33}S$(d,p)^{34}$S reaction,[4] implying negative parity. This level decays to the 0^+ ground state and the 2^+ level at 3.31 MeV.[24] Angular-correlation measurements[24] assign $J=1$ to this level. This level has also been identified in the ^{34}S$(p,p')^{34}$S reaction.[9] The $L=1$ angular distribution which is observed in the present work verifies the 1^- assignment of the 6.35-MeV level.

For the levels at 8.38 and 8.50 MeV no additional experimental information exists, since few experimental investigations of ^{34}S have extended this high in excitation. The $L=1$ angular distributions observed for these levels in the present experiment are sufficient, however, to determine 1^- spin and parity assignments.

F. $L=3$ transitions: States at 4.62 and 7.62 MeV

The angular distributions for the two levels shown in Fig. 7 have been fitted with $L=3$ DW calculations. These are the only two states that can be unambiguously identified as 3^- levels from the present data.

The level at 4.62 MeV is populated by an admixture of $l_n=1+3$ transitions in the ^{33}S$(d,p)^{34}$S reaction[4,16] and has also been identified in ^{37}Cl(p,α)-^{34}S[17] and ^{34}S$(p,p')^{34}$S.[9] This state decays to the 2^+ levels at 2.13 and 3.31 MeV[7,8,19]; angular-correlation measurements yield $J^\pi=3^-$.[19] The measured lifetime is 135 ± 17 fs.[18] The $L=3$ angular distribution observed in the present experiment also implies that the 4.62-MeV level is a 3^- state.

The ^{33}S$(d,p)^{34}$S reaction populates the level at 7.62 MeV by means of an $l_n=1$ transition[4]; the ^{34}S$(p,p')^{34}$S reaction also populates this level.[9] In the present experiment, an $L=3$ calculation reproduces the shape of the angular distribution well. Thus the 7.62-MeV level has spin and parity 3^-.

G. Doublet at 5.68 MeV in excitation

The doublet at 5.68 MeV was unresolved in the present experiment. The angular distribution for this doublet is shown in Fig. 8. We shall discuss each of the members of the doublet individually beginning with the higher excitation member.

The state at 5.69 MeV is populated by an $l_n=3$ transition in the ^{33}S$(d,p)^{34}$S reaction with such strength that this level must surely be the 5^- member of the $(d_{3/2}f_{7/2})$ multiplet.[4,16] This level decays to the 4^+ state at 4.68 MeV and to the 3^- state at 4.62 MeV[24]; angular-correlation measurements indicate that $J=5$ for this level. A polarization-direction correlation measurement also yields a 5^- assignment.[26] Because of these existing data, an $L=5$ distribution was chosen to fit the angular distribution of the doublet in Fig. 8.

TABLE II. Optical-model parameters (Refs. 11 and 12) used in the DW calculations.

	Set	V (MeV)	$r_0=r_{so}$ (fm)	$a=a_{so}$ (fm)	W (MeV)	$W'=4W_D$ (MeV)	r_0' (fm)	a' (fm)	V_{so} (MeV)	r_{oc} (fm)
Triton	I	177	1.138	0.724	14	0	1.602	0.769	5.0	1.40
Proton [a]	I	57.3	1.129	0.57	0	35.77	1.129	0.5	5.5	1.129
Bound state		···	1.26	0.60	···	···	···	···	$\lambda=25$	···

[a] The energy dependence of V, W', r_0 is given in Ref. 12.

TABLE III. Relative normalizations in ^{32}S$(t,p)^{34}$S.

E_x (MeV)	L	Configuration	$N=\sigma_{rel}/\sigma_{DW}$ (I,I)	$N=\sigma_{rel}/\sigma_{DW}$ (I,I')
0.00	0	$(d_{3/2})^2$	100	100
	0	$(s_{1/2})^2$	13.8	13.0
2.13	2	$(d_{3/2})^2$	11.8	11.5
	2	$d_{3/2}, s_{1/2}$	1.62	1.52
3.31	2	$(d_{3/2})^2$	9.12	8.79
	2	$d_{3/2}, s_{1/2}$	1.18	1.12
3.91	0	$(d_{3/2})^2$	3.62	3.33
	0	$(s_{1/2})^2$	0.48	0.42
	0	$(f_{7/2})^2$	1.75	2.18
4.12	2	$(d_{3/2})^2$	4.50	4.24
	2	$d_{3/2}, s_{1/2}$	0.59	0.53
	2	$(f_{7/2})^2$	2.25	2.61
4.62	3	$d_{3/2}, f_{7/2}$	33.8	33.3
	3	$d_{3/2}, p_{3/2}$	2.62	2.67
4.69	4	$(f_{7/2})^2$	2.00	1.88
	5	$d_{3/2}, f_{7/2}$	0.48	0.48
4.89	2	$(d_{3/2})^2$	3.50	3.30
	2	$(f_{7/2})^2$	1.88	1.88
5.22	0	$(d_{3/2})^2$	5.38	4.85
	0	$(f_{7/2})^2$	3.38	3.64
	0	$(p_{3/2})^2$	0.29	0.28
5.68	1	$d_{3/2}, p_{3/2}$	3.25	3.18
	5	$d_{3/2}, f_{7/2}$	2.12	2.18
5.76	1	$d_{3/2}, p_{3/2}$	9.38	8.18
5.86	0	$(f_{7/2})^2$	15.0	
6.01	2	$(f_{7/2})^2$	33.75	33.33
	2	$(p_{3/2})^2$	3.75	3.03
6.13	2	$(f_{7/2})^2$	7.75	7.88
6.18	3	$d_{3/2}, p_{3/2}$	0.22	0.21
	3	$d_{3/2}, f_{7/2}$	3.12	2.73
6.35	1	$d_{3/2}, p_{3/2}$	6.38	5.76
6.83	2	$(f_{7/2})^2$	4.25	4.55
	2	$(p_{3/2})^2$	0.42	0.36
7.11	3	$d_{3/2}, f_{7/2}$	11.25	10.00
	3	$d_{3/2}, p_{3/2}$	0.78	0.67
	2	$(f_{7/2})^2$	6.50	6.67
	2	$(p_{3/2})^2$	0.62	0.55
7.24	3	$d_{3/2}, f_{7/2}$	22.50	20.61
	3	$d_{3/2}, p_{3/2}$	1.62	1.52
7.62	3	$d_{3/2}, f_{7/2}$	23.75	23.03
	3	$d_{3/2}, p_{3/2}$	1.88	1.61
7.74	2	$(f_{7/2})^2$	4.75	5.15
	2	$(p_{3/2})^2$	0.48	0.39
7.80	2	$(f_{7/2})^2$	20.62	
8.02	0	$(p_{3/2})^2$	0.56	
8.25	2	$(f_{7/2})^2$	5.12	5.15
	2	$(p_{3/2})$	0.49	0.36
	3	$d_{3/2}, p_{3/2}$	0.62	0.52
	3	$d_{3/2}, f_{7/2}$	8.75	4.24
8.29	4	$(f_{7/2})^2$	4.75	4.85
	5	$d_{3/2}, f_{7/2}$	1.12	1.30
8.38	1	$d_{3/2}, p_{3/2}$	8.38	
8.42	4	$(f_{7/2})^2$	11.25	
8.50	1	$d_{3/2}, p_{3/2}$	12.25	

The other member of the doublet, the state at 5.68 MeV, is populated by an $l_n=1$ transition in the ^{33}S$(d,p)^{34}$S reaction.[4,16] This level decays to the 2^+ level at 2.13 MeV and angular correlation measurements[24] indicate that it is a 2^- level. Figure 8 illustrates that the angular distribution of the doublet can be satisfactorily fitted by a mixture of $L=1$ and $L=5$ DW calculations. This suggests that the state at 5.68 MeV may be a 1^- level. However, the angular-correlation measurement is probably sounder, if it was not influenced by the possible $l_n=(3)$ of Ref. 16.

H. States at 6.18, 7.11, 7.24, and 8.25 MeV

For these four levels, whose angular distributions are shown in Figs. 7 and 9, it is difficult to distinguish from the DW calculations whether the angular distributions are characteristic of $L=2$ or $L=3$. In Fig. 9 the distributions of two of these states have been fitted with both of these possible L values.

The evidence bearing on the spin and parity of the 6.18-MeV level is somewhat conflicting. In their investigation of the ^{35}Cl$(d,{}^3$He$)^{34}$S reaction, Wildenthal and Newman[14] identify the angular distribution of this level as $l_p=2$. From the mixed $l_n=1+3$ angular distribution in the ^{33}S$(d,p)^{34}$S reaction, Crozier[4] assigned negative parity to this level and suggested that it may be the analog of the 6.17-MeV 3^- $T=1$ resonance in ^{34}Cl. Jones *et al.*[24] observed the decay of this level to the 2^+ states at 2.13, 3.31, and 4.89 MeV and to the 4^+ level at 4.69 MeV; from angular-correlation measurements these authors conclude $J=3$ and suggest positive parity. The angular distribution from the ^{32}S$(t,p)^{34}$S reaction, which is shown in Fig. 7, does not shed a great deal of light upon this matter. The distribution is rather structureless and nearly

TABLE IV. Summary of spectroscopic information on ^{34}S.

E_x (MeV)	(t,p) [a] L	(d,p) l_n	$(d,{}^3He)$ l_p	γ decay Branches	$t_{1/2}$	J	J^π
0.00	0	2 [b,c]	2 [d,e]				0^+
2.13	2	0,2 [b,c]	0,2 [d,e]	0^+	400 ± 32 fs [f]	2 [g,h]	2^+
3.31	(2)	0,2 [b,c]	0 [d,e]	$0^+,2^+$ [g,h,i,j]	190 ± 40 fs [k]	2 [g,h]	2^+
3.92	0			2^+ [g,h,j]	1600 ± 130 fs [j]	≤4 [g]	0^+
4.08		0,2 [b]	0 [d,e]	$0^+,2^+$ [g,h,j]	< 24 fs [f]	1 [g,h]	1^+
4.12	2	0,2 [b,c]		$0^+,2^+$ [g,h,j]	110 ± 10 fs [f]	2 [h]	2^+
4.62	3	1,3 [b,c]		2^+ [g,h,j]	135 ± 17 fs [f]	3 [h]	3^-
4.69	(4)		2 [d,e]	2^+ [g,h,j]	131 ± 13 fs [f]	4 [h]	4^+
4.88 } [l]	(2)	(1,3) [b]	2 [d,e]	2^+ [g,h,j]	57 ± 22 fs [f]	3 [h]	3
4.89 }				$0^+,2^+$ [g,h,j]	52 ± 14 fs [f]	2 [g,h]	2
5.22	0			1^+ [h]		(0) [h]	0^+
5.68 } [l]	5(1)	1 [b,c]		2^+ [m]		2 [m]	$2^-(1^-)$
5.69 }		3 [b,c]		$3^-,4^+$ [m]	54 ± 5 ps [n]	5 [m,n]	5^-
5.76	1	1 [b,c]					1^-
5.86	0						0^+
6.01	2			$0^+,2^+$ [m]		2 [m]	2^+
6.13	2			2^+ [m]		(1,2) [m]	2^+
6.18	(3)	1,3 [c]	2 [d]	$2^+,4^+$ [m]		3 [m]	3^-
6.35	1	1 [c]		$0^+,2^+$ [m]		1 [m]	1^-
6.74				$2^+,4^+$ [m]			$2^+,4^+$
6.83	2	0 [c]	0 [d]	$0^+,2^+,3$ [m]		2 [m]	2^+
7.11 [o]	3(2)	1,3 [c]	0 [d]	$0^+,2^+$ [m]		2 [m]	3^- (and 2^+)
7.24	2 or 3		2	$0^+,2^+$ [m]		2 [m]	2^+
7.39	3			5^- [m]			3^-
7.62	3	1 [c]					3^-
7.74	2	(1,3)					2^+
7.80	2						2^+
8.02	0						0^+
8.25	2						2^+
8.29	(4)						
8.38	1						1^-
8.42	4						4^+
8.50	1						1^-

[a] Present work.
[b] Reference 16.
[c] Reference 4.
[d] Reference 14.
[e] Reference 15.
[f] Reference 18.
[g] Reference 7.
[h] Reference 19.
[i] Reference 21.
[j] Reference 8.
[k] Reference 23.
[l] Doublet not resolved in the present work.
[m] Reference 24.
[n] Reference 26.
[o] Possible doublet (see text).

symmetric, suggesting a compound process and a possible unnatural parity state. On the other hand, the total cross section for this level is about five times as large as that for the 4.08-MeV 1^+ state which, for a compound mechanism, would imply a spin of 7 if a $(2J+1)$ dependence is assumed. Other possibilities are that an unnatural parity level might be populated via a direct spin-flip mechanism or that this state may be a doublet.

The transition to the 7.11-MeV level has been observed to have $l_p = 0$ in the $^{35}Cl(d, {}^3He)^{34}S$ reaction.[14] (However, this angular distribution consists of few points, and no odd parity distributions are shown in this paper. Thus it is difficult to determine whether the possibility of $l_p = 1$ may be eliminated.) However, in the $^{33}S(d,p)^{34}S$ reaction,[4] a mixture of $l_n = 1$ and $l_n = 3$ transitions populate this level, implying that it has $J^\pi = (2,3)^-$. The 7.11-MeV level has been observed to decay to the 0^+ ground state and to the 2^+ levels at 2.13 and 3.31 MeV; angular-correlation measurements[24] assign $J = 2$ to this level. In view of the conflicting parity assignments, it was hoped that the present data would provide a satisfactory determination. Unfortunately the first maximum of the angular distribution lies almost exactly between the position predicted by the DW calculations for $L = 2$ and $L = 3$ angular distributions. Because of the tendency of the DW calculations to predict the structure to occur at slightly more backward angles than observed in experimental data, the analysis favors $L=3$, which would imply a 3^- assignment. Thus the existence of a 3^- state at this excitation seems to be verified. However, this cannot account for the decay branch to the 0^+ ground state. The simplest conclusion is that this level may be a doublet consisting of 2^+ and 3^- members.

The ^{35}Cl$(d,{}^3$He$)^{34}$S reaction[15] populates the 7.24-MeV level by means of an $l_p=2$ transition. This level decays to the 0^+ ground state and the 4^+ state at 4.68 MeV; this branching implies that the level is 2^+. The 7.24-MeV level has also been identified in the ^{34}S$(p,p')^{34}$S[9] and ^{33}S$(d,p)^{34}$S[4] reactions. It is difficult to assign an L value to the angular distribution obtained in the ^{32}S$(t,p)^{34}$S reaction. The best fit is obtained when an $L=3$ calculation is employed. However, it should be pointed out that the experimental distribution is similar in shape to that of the 3.31-MeV 2^+ level. Thus the existing 2^+ assignment is probably correct.

No other information pertaining to the 8.25-MeV level exists. The distribution for this level is also between those generally observed for $L=2$ and $L=3$ transitions, but in this case the $L=2$ transition is definitely to be favored. Since there is no conflicting information to be considered, we suggest $J^\pi=(2^+)$ for the 8.25-MeV level.

I. States at 4.08 and 6.74 MeV in excitation

The ^{35}Cl$(d,{}^3$He$)^{34}$S reaction[14,15] populates the 4.08-MeV level by an $l_p=0$ transition. The ^{33}S$(d,p)^{34}$S reaction[16] populates it by $l_n=0$ and $l_n=2$. This level decays[7,8,19] to the 0^+ ground state, and to the 2^+ levels at 2.13 and 3.31 MeV; angular-correlation measurements[7,19] yield $J=1$. The lifetime is less than 24 fs.[18] This level is only weakly populated with a nearly symmetric angular distribution in the ^{32}S$(t,p)^{34}$S reaction (Fig. 10) as would be expected for an unnatural parity level (i.e., 1^+). This state has also been identified in the ^{34}S$(p,p')^{34}$S[9] and the ^{37}Cl$(p,\alpha)^{34}$S[17] reactions.

The state at 6.74 MeV decays to the 2^+ levels at 2.13 and 3.31 MeV, the 4^+ level at 4.69 MeV, and the state at 4.89 MeV, and a 2^+ or 4^+ assignment is indicated.[24] The angular distribution observed in the present experiment cannot be identified with any L value. The total cross section is eight times that of the 4.08-MeV level, however, indicating that this level is probably of natural parity. The 4.08-MeV level has also been observed in the ^{34}S$(p,p')^{34}$S reaction.[9]

J. Configuration dependence

Some qualitative differences in the shapes of the angular distributions of states populated with the same L-value transition are observed in the present experiment. These differences may be caused by the different configurations into which the two neutrons are transferred for the different levels. It was noted[27] that the DW calculations for different configurations also varied, often in a way similar to that of the experimental distributions. For example, the angular distribution for the 0^+ level at 5.86 MeV is shown in Fig. 11, where it has been fitted with DW calculations for three possible configurations $(d_{3/2})^2$, $(p_{3/2})^2$, and $(f_{7/2})^2$. This level has been identified[20] as the 0^+ member of the $(f_{7/2})^2$ multiplet, and it can be seen in Fig. 11 that the $(f_{7/2})^2$ configuration does, in fact, reproduce the shape of the second maximum qualitatively better than the other two configurations.

V. CONCLUSIONS

In Fig. 12, the experimental level scheme of ^{34}S is compared with results of two recent calculations for the positive parity levels. The calculations of Wildenthal *et al.*[28] are shown on the left while those of Castel *et al.*[29] are shown on the right. The experimental levels which have been identified as negative parity have been omitted from Fig. 12; those with undetermined parity have been indicated by broken lines. Below 5.4 MeV the correspondence between the experimental and theoretical levels is good. Above this excitation it is more difficult to identify the corresponding levels since the spins and parities of many of the levels have not been unambiguously determined, and many levels which have no counterparts within the shell-model scheme are expected. Note that the 5.86-MeV 0^+ level is the $(f_{7/2})^2$ level and there-

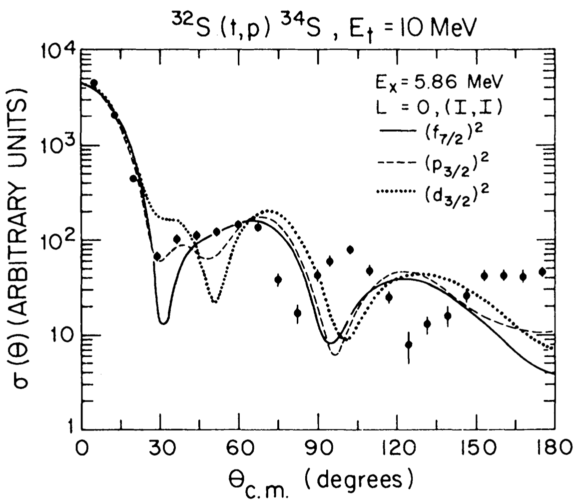

FIG. 11. Angular distributions of the 5.86-MeV 0^+ state fitted with DW calculations for three possible bound state configurations—solid and broken lines.

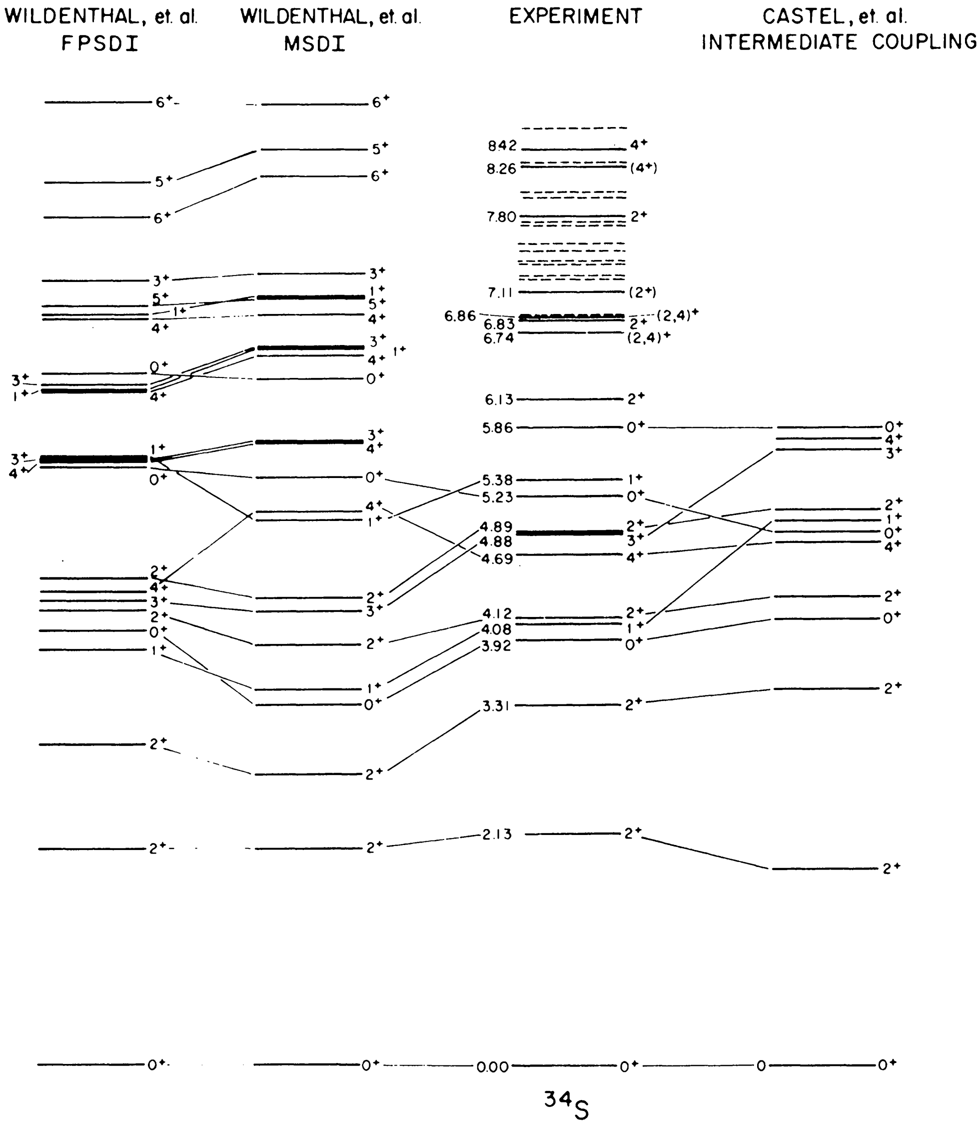

FIG. 12. Comparison of experimental level scheme of ^{34}S with theoretical calculations for the positive parity states. Negative parity states have been suppressed in the experimental level scheme; states of unknown parity are indicated by broken lines.

fore not the fourth 0^+ level predicted by Wildenthal *et al.*[28]

In summary, the convenient selection rules of the (t,p) reaction and the powers of DW analysis make it possible to draw several conclusions from the present experiment. First, many spin and parity assignments have been substantiated and some new assignments have been made. In addition we have noted that the level at 7.11 MeV is probably a doublet. From the convenience of (t,p) reactions for studying two-particle states, three probable members of the $(f_{7/2})^2$ multiplet have been identified[20] and they are in good agreement with other $(f_{7/2})^2$ multiplets in ^{42}Ca, ^{42}Sc, and ^{48}Sc. Finally, it was noted[27] that possible configuration dependence may be observed in the angular distributions from the $^{32}S(t,p)^{34}S$ reaction.

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