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^{32}Si from ^{30}Si(t,p)

H. T. Fortune and L. Bland
Physics Department, University of Pennsylvania, Philadelphia, Pennsylvania 19104

D. L. Watson and M. A. Abouzeid*
Postgraduate School of Studies in Physics, University of Bradford, Bradford, BD7 1DP, United Kingdom
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In the ^{30}Si(t,p) reaction at a bombarding energy of 15.0 MeV, excitation energies have been measured for 53 levels up to $E_x = 11.5$ MeV. Angular distributions for 29 levels below 8.8 MeV have been compared with distorted-wave Born approximation calculations in order to make L (and hence J^π) assignments. Measured cross sections are compared with absolute predictions with distorted-wave Born approximation calculations that use two-nucleon transfer amplitudes from a full sd-shell-basis shell-model calculation.

[NUCLEAR REACTIONS ^{30}Si(t,p)^{32}Si; $E = 15$ MeV; measured $\sigma(E_p,\theta)$, $\theta = 7.5° - 105°$. ^{32}Si levels. DWBA microscopic analysis.]

I. INTRODUCTION

Information on $T_Z = 2$ nuclei in the middle of the $1d$-$2s$ shell is still very scant. For example, in ^{32}Si only three states have definite J^π assignments.[1] The (t,p) reaction provides an ideal method of investigating such nuclei. An early study[2] of ^{30}Si(t,p) obtained excitation energies for 10 levels in ^{32}Si, and the same reaction was subsequently used as a way of populating ^{32}Si levels in order to investigate their γ decays.[3,4] In the latest compilation,[1] no other reaction is reported to have produced excited states of ^{32}Si.

The present paper reports results of a high-resolution study of the ^{30}Si(t,p) reaction to levels up to 11.5 MeV excitation in ^{32}Si. Angular distributions were obtained for 29 levels below 8.8 MeV excitation. Comparison of these with predictions of microscopic distorted-wave Born approximation (DWBA) calculations has enabled L and hence J^π determinations for most of these states.

II. EXPERIMENTAL PROCEDURE

The experiment was performed in the University of Pennsylvania FN tandem accelerator with a 15-MeV triton beam from a sputter ion source[5] incident on a self-supporting ^{30}Si target (enrichment 95.6%) of about 24 μg/cm^2 areal density. Outgoing protons were momentum analyzed in a multiangle spectrograph and detected in nuclear emulsion plates. Thick Mylar absorbers immediately in front of the focal planes stopped all particles except protons.

A monitor detector placed 40° to the incident beam direction measured elastically scattered tritons. Normalization of this data to elastic-scattering measurements performed elsewhere[6] provided the absolute cross-section scale, which we estimated to be uncertain to about 15%.

The plates were scanned with the aid of the automatic scanner at the University of Bradford. The details of the scanner and its comparison with manual scanning are given in full elsewhere.[7] Checks on the automatic scanning were made by human observers on several groups covering the whole excitation range of the data. In all cases the agreement was well within the 5% range normally associated with manual scanning.

III. RESULTS

A spectrum is displayed in Fig. 1. The resolution is 19 keV (FWHM). The level numbering scheme is that of Tables I and II, which list average excitation energies obtained from measured peak positions and the spectrograph calibration. The observed impurity peaks are due to ^{12}C, ^{16}O,

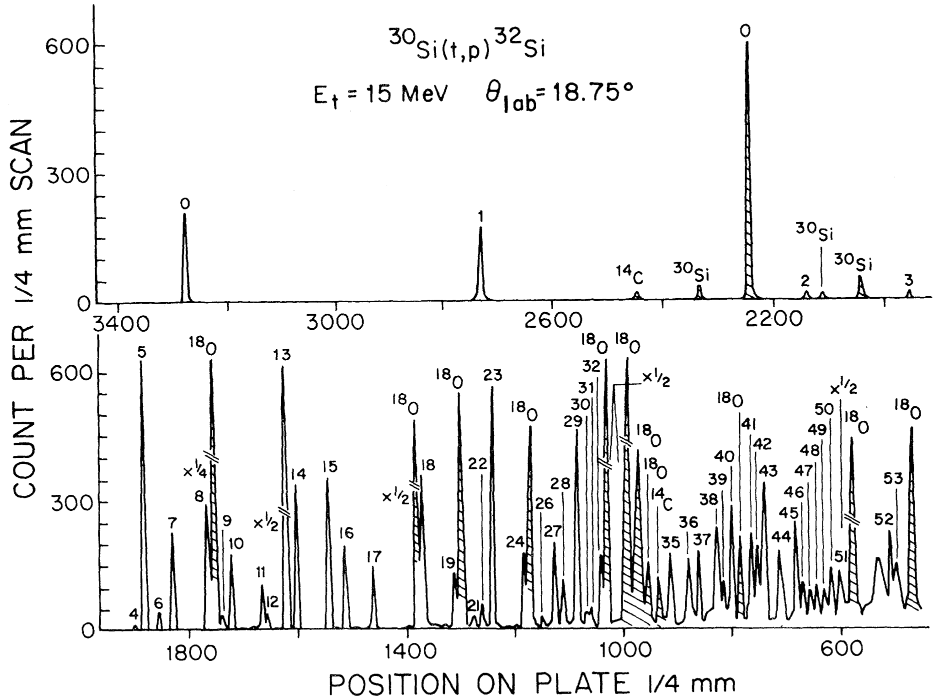

FIG. 1. Spectrum of the $^{30}Si(t,p)^{32}Si$ reaction at a bombarding energy of 15.0 MeV and a laboratory angle of 18.75°. Levels in ^{32}Si are numbered consecutively, beginning with zero for the gound state. Impurity groups arising from the (t,p) reaction on ^{12}C, ^{16}O, and ^{28}Si are hatched and labeled by final nucleus.

and ^{28}Si in the target material. The identification of peaks arising from impurities is facilitated by the systematic variation of their calculated excitation energies from angle to angle when kinematics for the $^{30}Si(t,p)^{32}Si$ reaction are used. Above 8.8 MeV excitation, data were analyzed for only a few forward angles. Below that energy, angular distributions were obtained for the angular range 3.75° to 86.25° (lab) in steps of 7.5°. These are displayed in Figs. 2 and 3.

Below 6.7 MeV, our excitation energies can be compared with values from the compilation. Above that energy, all our states are reported here for the first time. For most states below 6.7 MeV, a one-to-one correspondence between our states and those in the literature is obvious; for these states our excitation energies agree reasonably well with those in the compilation, although our values tend to be consistently higher than the compiled ones by 2–13 keV. In at least two cases in which the discrepancy in energy is larger, the J^π values deduced herein (see below) also disagree with values from the literature so that it is likely that we are observing different states. In addition, two levels at 5893 ± 8 and 6477 ± 6 keV appear to have no counterparts in the literature.

IV. ANALYSIS

At least two shell-model calculations for ^{32}Si exist — one in a truncated space,[8] the other in a complete $1d$-$2s$ basis.[9] From their γ-decay properties, the two 2^+ states at $E_x=1.94$ and 4.23 MeV, and a tentative[3] (0^+) level at 4.98 MeV, appear[3] to be in good agreement with the shell-model calculations, the latest of which[9] puts 2^+ states at 2.25 and 4.28 MeV and a 0^+ level at 4.78 MeV. Above 5.0 MeV, no correspondence could be established between shell-model and experimental states by Ref. 3.

We have performed DWBA calculations for all the angular distributions displayed in Figs. 2 and 3, using the microscopic two-nucleon-transfer option of the code DWUCK[10] and the optical-model parameters[11] listed in Table III. Calculations were performed with shell-model transfer amplitudes[9] and for a variety of pure two-neutron configurations. Predicted curves were compared with the

TABLE I. Results of the ^{30}Si(t,p)^{32}Si reaction compared with previous information on ^{32}Si.

Previous E_x (keV)	Previous J^π	Present No.	Present E_x (keV)	σ_{max}(mb/sr)	L	Remarks
0	0^+	0	0	3.97	0	
1941.4±0.3	2^+	1	1943±5	0.31	2	
4232 ±3	2^+	2	4239±8	2.9×10^{-2}	2	
4983 ±3	(0^+)	3	4996±9	0.23	0	$J^\pi=0^+$ assigned
5220 ±3	(1−4)	4	5229±3	2.3×10^{-2}		May be 1^+
5288.8±0.8	3	5	5295±5	0.88	3	$J^\pi=3^-$ assigned
5412.4±0.9	1					
		6	5427±14	7.5×10^{-2}	2	$J^\pi=2^+$ assigned
5502 ±4		7	5509±5	0.38	(5)	Probably $J^\pi=5^-$
5773 ±2	(1−3)	8	5786±6	(0.59)	(0)	$J^\pi=(0^+)$ for one member
5791 ±2						
		9	5893±8	7.3×10^{-2}		May be 3^+
5954 ±2	2					
		10	5967±4	0.25	3	$J^\pi=3^-$ assigned
6170 ±5						
6195 ±4	1	11	6208±9	0.25	1+2	1^- and 2^+ doublet
6242 ±5		12	6256±8	0.29	0	$J^\pi=0^+$ assigned
6388 ±3	2	13	6394±6	2.20	2	$\pi=+$ assigned
		14	6477±6	0.50	3	$J^\pi=3^-$ assigned
6705 ±6	1					
		15	6734±9	1.4	1	$J^\pi=1^-$
		16	6860±5	0.29	3	$J^\pi=3^-$
		17	7083±5	0.23	2	$J^\pi=2^+$
		18	7482±9	(0.73)		
		19	7743±6	(0.10)		
		20	7793±9	1.3	3 or 4	$J^\pi=3^-$ or 4^+
		21	7887±18	8.4×10^{-2}		
		22	7978±14	8.2×10^{-2}	3	$J^\pi=3^-$
		23	8066±9	0.92	2	$J^\pi=2^+$
		24	8321±8	0.19	5	$J^\pi=5^-$
		25	8361±10	1.1	2	$J^\pi=2^+$
		26	8422±10	no ang. distrib.		
		27	8567±8	0.29	3	$J^\pi=3^-$
		28	8650±15	0.20	2	$J^\pi=2^+$
		29	8758±9	0.67	3 or 4	$J^\pi=3^-$ or 4^+

data in order to extract L values and enhancement factors ϵ (listed in Table IV), defined by

$$\sigma_{\exp}(\theta)=N\epsilon\sigma_{L,\mathrm{DWBA}}(\theta) .$$

Earlier work with this potential combination has established[12] $N\approx390$, and we use this value to extract ϵ values.

The gound-state angular distribution has a clear $L=0$ shape. In light of the configuration-dependent $L=0$ shapes discussed below and the dominance of $(fp)^2$ transfer over $(sd)^2$ transfer whenever both are present, the presence of a secondary maximum near 30° in the g.s. angular distribution implies virtually *no* fp-shell admixture into the ^{32}Si(g.s.) wave function. This conclusion is supported by the value of $\epsilon=1.6$ extracted for the g.s.

The two 2^+ states at 1.94 and 4.24 MeV differ in measured cross section by a factor of 10, but the DWBA calculations with Chung-Wildenthal (CW) amplitudes for the 2_1^+ and 2_2^+ shell-model states differ only by a factor of 2. Thus, the extracted ϵ value is too large for the first 2^+ state and too small for the second. Similar difficulties in fitting relative magnitudes of (t,p) cross sections to 2^+ states has been noted[13] for ^{32}S$(t,p)^{34}$S.

The state of 4996 keV is assigned $J^\pi=0^+$ in the present work, but it is too strong and its angular

TABLE II. Higher-lying levels of ^{32}Si.

No.	E_x (keV)	Angles
30	8842±13	1,5,6
31	8877± 8	1,3–5
32	8971± 9	3,5,6
33	9003± 7	4–6
34	9192±12	4–6
35	9543± 6	2–5
36	9701± 6	2–4
37	9782±12	2–6
38	9934±29	2–5
39	9975±25	2–5
40	10052± 5	2–5
41	10237± 5	2–5
42	10279± 6	2–4
43	10317± 5	2–5
44	10461± 9	2,3
45	10603±15	2–6
46	10664±14	2–6
47	10725± 9	2–5
48	10778±13	2–6
49	10846±13	2–4
50	10888±12	2–5
51	10971± 9	2–5
52	11398± 7	2–5
53	11454± 8	2–5

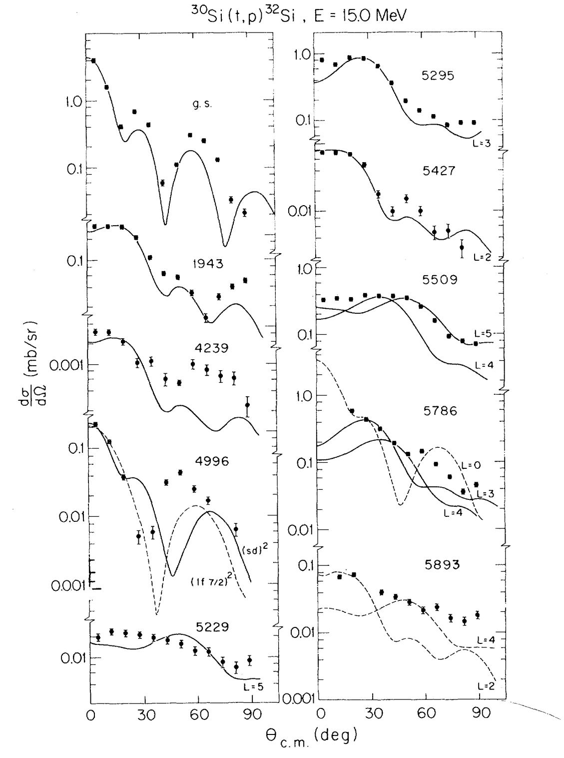

FIG. 2. Angular distributions for the ^{30}Si(t,p) reaction leading to levels in ^{32}Si. Curves are results of distorted-wave calculations, as discussed in the text.

distribution has the wrong shape to be a pure sd-shell state. DWBA calculations for $(1f_{7/2})^2$ $L=0$ transfer produce shapes with no hint of a maximum near 30°, whereas those for $(sd)^2$ transfer possess a maximum there. This effect has been noted before[14] in this mass region. The experimental angular distribution for the 5.0-MeV state has no maximum near 30°. Also, it is about three times as strong as the CW(0_2^+) state should be. Both features suggest the presence of a small $(fp)^2$ admixture into the wave function for this state. A transfer configuration of $\sqrt{0.2}(1f_{7/2})^2$ would produce all of the observed cross section, so that the necessary admixture is smaller than 20%. The third 0^+ sd-shell state is predicted very nearby, at 5.19 MeV, but it is calculated to be very weak in (t,p)— about $\frac{1}{4}$ as strong as CW(0_2^+).

The state at 5229 keV has a rather featureless angular distribution, not characteristic of any single L transfer. We compare the data with an $L=5$ curve (the resulting fit is poor, but better than any other L value), but a 5^- assignment would contradict limits[1] $J=1-4$ set by γ-decay work.[3,4] It is likely that this state has unnatural parity. It is the weakest state observed in the present work. The

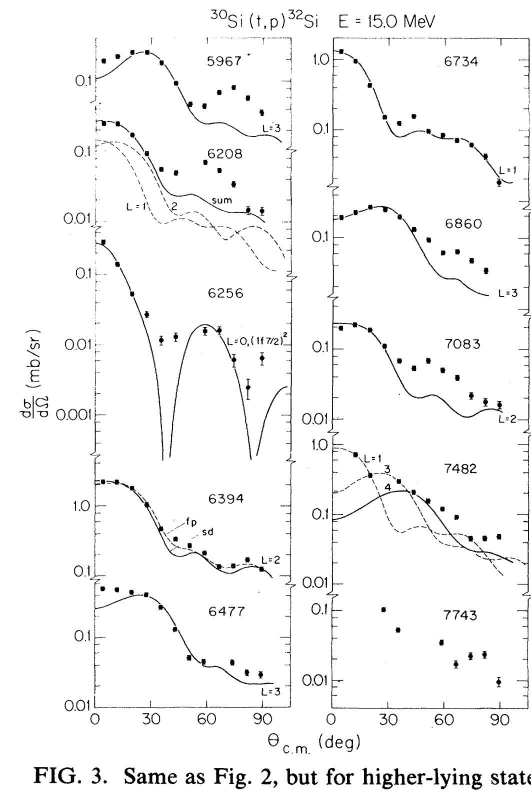

FIG. 3. Same as Fig. 2, but for higher-lying states.

TABLE III. Optical-model parameters used in DWBA analysis of ^{30}Si$(t,p)^{32}$Si. Potentials in MeV, lengths in fm.

	V	r_0	a	W	W'	r_0'	a'	V_{so}	r_C
t	162.9	1.18	0.69	17.9		1.50	0.82	0.0	1.18
p	54.0	1.25	0.65		69.0	1.25	0.47	0.0	1.25
bs	varied	1.26	0.6					$\lambda=25$	1.26

shell-model calculations predict a 1^+ state at 5.37 MeV. This may be it.

The state we observe at $E_x=5295\pm5$ keV, with an unambiguous $L=3$ angular distribution, is clearly to be associated with the state at 5288.8 ±0.8 keV,[1,4] assigned $J=3$ in Ref. 3. In fact, Ref. 3 states a preference for negative parity. Negative parity, of course, requires excitations outside the *sd* shell, and the large (t,p) cross section can arise only from excitation into the *fp* shell. In fact, the 5.3-MeV 3^- state has about twice the cross section expected for a pure $(1d_{3/2})(1f_{7/2})$ $L=3$ transfer, indicating some configuration mixing.

The state we observe at 5427 ± 14 keV has an unmistakable $L=2$ angular distribution, and hence is unlikely to be the state listed in the compilation[1] at 5412 keV, with $J=1$. We assign $J^\pi=2^+$ to the state we observe. Its cross section lies between that observed for the first and second 2^+ states. The shell model[9] puts the third 2^+ level at 5.38 MeV (very close to the observed energy of 5.43 MeV), but the observed state is only one-tenth as strong as the CW(2_3^+) is predicted to be — further confirmation of the inability of the shell model to reproduce the mixing among the low-lying 2^+ states.

The state we observe at 5509 ± 5 keV is moderately strong and has an angular distribution characteristic of either $L=4$ or 5, with some preference for the latter. The shell model puts a 4^+ level at 5.58 MeV, but the present cross section is three times as large as that predicted for this CW(4^+) state. In fact, it is more than twice as strong as the combined $L=4$ strength of all the *sd*-shell 4^+ states. Hence, we strongly favor $J^\pi=5^-$ for the 5.5-MeV state. A state is listed at 5502 ± 4 keV in the compilation, but with no J^π information. Finding a 5^- level just above the lowest 3^- state would not be surprising since $(1d_{3/2})(1f_{7/2})$ can couple to 5^-. The measured cross section for the 5.5-MeV state is about one-fifth of that calculated for a pure $(1d_{3/2})(1f_{7/2})$ $L=5$ transfer.

Our 5786 ± 6 keV state corresponds to a doublet, one member of which probably has $J^\pi=0^+$, from an apparent $L=0$ component in the combined angular distribution. The assignment is not definite, because the extreme forward angles are obscured by an oxygen impurity. The compilation lists two states near here, one at 5773 ± 2 keV, with $J=(1-3)$, and the other at 5791 ± 2 keV. If one member is indeed 0^+, it contains virtually 100% of the $(1f_{7/2})^2$ 0^+ strength, and is much too strong to be identified with the third *sd*-shell 0^+ state, predicted at 5.19 MeV. The other member of this doublet is a candidate for either the 4_1^+ or 3_1^+ shell-model states, predicted at 5.58 and 5.92 MeV, respectively.

Our 5893 ± 8 keV level has no counterpart in the complication, and its angular distribution is not characteristic of any single L value. It may thus be a doublet or an unnatural-parity state. If one member of the 5.8-MeV doublet has $J^\pi=4^+$, then the 5.9-MeV level is an excellent candidate for the first 3^+ level predicted[9] at 5.92 MeV.

The compilation lists a $J=2$ level at 5954 ± 2 keV. Our 5967 ± 4 keV state possesses an unambiguous $L=3$ angular distribution, giving a $J^\pi=3^-$ assignment. Thus, they must be different states. This second 3^- state is about 30% as strong as the lower one at 5.29 MeV.

The state we observe at 6208 ± 9 keV is a doublet, and its angular distribution appears to be an admixture of $L=1$ and 2. The compilation lists two states near here, one at 6195 ± 4 keV, with $J=1$, and the other at 6170 ± 5 keV. If these are the same two states as the two we observe, then $J^\pi(6170)=2^+$ and $J^\pi(6195)=1^-$. The 1^- member is resonably weak, having about 14% of the cross section expected for a pure $(1d_{3/2})(2p_{3/2})$ $L=1$ transfer. The 2^+ member has about the right strength to be identified with the fourth *sd*-shell 2^+ state, expected near 6.92 MeV.

The state observed at 6256 ± 8 keV, though weak, has a clear $L=0$ angular distribution, with only a hint of a shoulder near 30°. Thus $J^\pi=0^+$ and the configuration of the transferred pair of neutrons

TABLE IV. Comparison of experiment and theory for $^{30}Si(t,p)^{32}Si$.

Experiment		Theory		
E_x (MeV)	J^π	E_x (MeV)	Configuration	ϵ
0.0	0^+	0.0	$CW(0_1^+)$	1.6
1.94	2^+	2.25	$CW(2_1^+)$	5.3
4.24	2^+	4.28	$CW(2_2^+)$	0.86
5.00	0^+	4.78	$CW(0_2^+)$	4.6
			$(1f_{7/2})^2_{0^+}$	0.32
		5.19	$CW(0_3^+)$	18
5.23		5.37	$CW(1_1^+)$?	
5.29	3^-		$[(1d_{3/2})(1f_{7/2})]_{3^-}$	3.4
5.43	2^+	5.38	$CW(2_3^+)$	0.17
			$(1f_{7/2})^2_{2^+}$	0.16
5.51	4^+	5.58	$CW(4_1^+)$	4.9
	or 5^-		$[(1d_{3/2})(1f_{7/2})]_{5^-}$	0.32
5.78	$0^+ + ?$	5.19	$CW(0_3^+)$	260
			$(1f_{7/2})^2_{0^+}$	2.1
		5.58	$CW(4_1^+)$	3.0
5.89	no fit	5.92	$CW(3_1^+)$	
5.97	3^-		$[(1d_{3/2})(1f_{7/2})]_{3^-}$	0.97
6.21	1^-		$[(1d_{3/2})(2p_{3/2})]_{1^-}$	0.23
	and 2^+	5.38	$CW(2_3^+)$	0.29
		6.92	$CW(2_4^+)$	1.9
			$(1f_{7/2})^2_{2^+}$	0.60
6.26	0^+		$(1f_{7/2})^2_{0^+}$	0.30
6.39	2^+	6.92	$CW(2_4^+)$	31
			$[(1f_{7/2})(2p_{3/2})]_{2^+}$	0.45
6.48	3^-		$[(1d_{3/2})(1f_{7/2})]_{3^-}$	1.2
6.73	1^-		$[(1d_{3/2})(2p_{3/2})]_{1^-}$	2.1
6.86	3^-		$[(1d_{3/2})(1f_{7/2})]_{3^-}$	0.97
7.08	2^+	6.92	$CW(2_4^+)$	3.3
7.48		7.07	$CW(4_2^+)$	32
7.79	3^-		$[(1d_{3/2})(1f_{7/2})]_{3^-}$	4.8
	or 4^+	8.36	$CW(4_3^+)$	54
7.98	3^-		$[(1d_{3/2})(1f_{7/2})]_{3^-}$	0.27

TABLE IV. (*Continued.*)

8.07	2^+		$(1f_{7/2})^2_{2^+}$	2.0
8.32	5^-		$[(1d_{3/2})(1f_{7/2})]_{5^-}$	0.11
8.36	2^+		$(1f_{7/2})^2_{2^+}$	2.4
8.57	3^-		$[(1d_{3/2})(1f_{7/2})]_{3^-}$	1.0
8.65	2^+		$(1f_{7/2})^2_{2^+}$	0.51
8.76	3^-		$[(1d_{3/2})(2p_{3/2})]_{3^-}$	0.14
	or 4^+	8.61	CW(4^+_4)	270

has both $(sd)^2$ and $(fp)^2$ components. This state has only about 20% of the expected strength for $(1f_{7/2})^2$ $L=0$ transfer. It is very likely that this state and the two 0^+ levels at 5.0 and 5.8 MeV are linear combinations of the second and third *sd*-shell 0^+ states and the first $(fp)^2$ 0^+ level.

Our 6394±6 keV state is second in strength only to the g.s. and has an $L=2$ angular distribution, implying $J^\pi=2^+$. It is much too strong to be associated with any *sd*-shell 2^+ level, but must be dominated by *fp*-shell admixtures. It is about 30% of the cross section expected for a pure $(1f_{7/2})(2p_{3/2})$ 2^+ transfer. A small amount of configuration dependence is noted in $L=2$ DWBA shapes, as may be seen by comparing *fp* and *sd* shapes for the 6.39-MeV level. However, the difference is only slight. A state at 6388±2 keV was already known[1] to have $J=2$.

Our 6477±6 keV state, to which we assign $J^\pi=3^-$ on the basis of an $L=3$ angular-distribution shape, has no counterpart in the literature. Its cross section is abour 80% of that for a pure $(1d_{3/2})(1f_{7/2})$ $L=3$ transfer.

We observe a strong 1^- state at 6734±9 keV, with a cross section somewhat larger than that corresponding to a pure $(1d_{3/2})(2p_{3/2})$ $L=1$ transfer. The compilation lists a $J=1$ level at 6705±6 keV.

Above this energy all our results are new, and there is nothing in the compilation to compare them to (see Table I). We observe 3^- states at 6.86, 7.98, and 8.57 MeV; 3^- or 4^+ levels at 7.79 and 8.76 MeV; four 2^+ levels at 7.08, 8.07, 8.36, and 8.65 MeV; and a 5^- state at 8.32 MeV. We are unable to make assignments to levels at 7482±9, 7743±6, 7887±18, and 8422±10 keV. The first and third of these each appear to correspond to more than one state, the angular distribution for the second is incomplete because of impurities, and there is no angular distribution for the fourth.

In Fig. 5, we depict in columns 3 and 4 the predicted shell-model energies for all levels between 4.78 and 9.02 MeV excitation. Column 4 contains the unnatural-parity levels, and column 3 contains the natural-parity ones. In column 2 we list all states with definite or probable positive parity and even spin. Column 1 contains all additional levels not known to have negative parity. In many cases, the correspondence between experiment and shell model is clear. Also clear in the experimental spectrum is the presence below 7.5 MeV of one more 0^+ and one more 2^+ level than predicted in a complete *sd*-shell model space. These undoubtedly correspond to $(fp)^2$ excitation, as discussed above. No clear experimental candidates exist for the higher-lying 0^+ and 4^+ shell-model states. It also

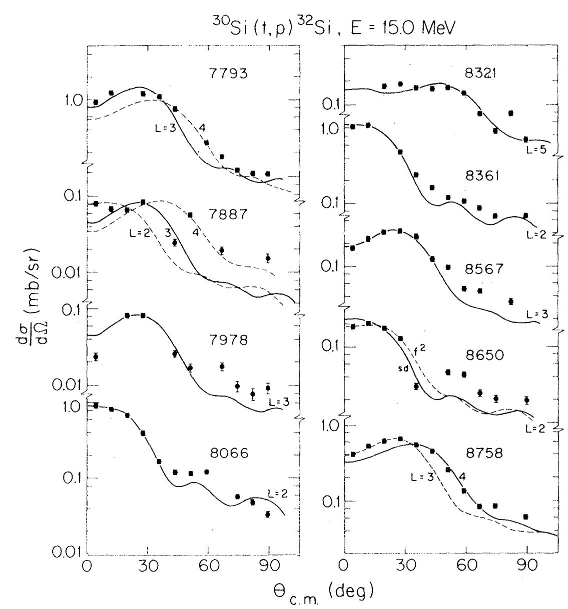

FIG. 4. Same as Fig. 2, but for higher-lying states.

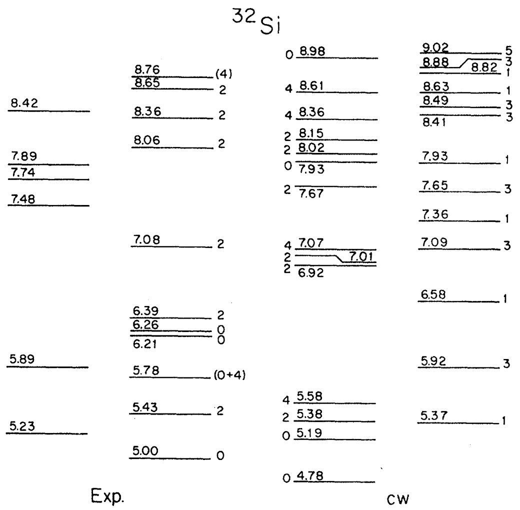

FIG. 5. Comparison of experimental (left) and theoretical (right) energy levels in ^{32}Si. Column 2 contains firm or probable even-spin positive-parity levels, and column 1 contains other levels not known to have negative parity. Columns 3 and 4 list the even- and odd-spin states, respectively, from an *sd*-shell-model calculation (Ref. 6).

appears that the present experiment has missed a number of odd-spin, positive-parity levels, presumably because they are weak in (t,p).

V. SUMMARY

Analysis of the ^{30}Si$(t,p)^{32}$Si reaction has yielded 17 new spin and parity assignments for levels in ^{32}Si. We also have confirmed the spin and parity of eight other levels. For the positive parity states comparison was made with a full $1d$-$2s$ space shell model calculation. There is generally good agreement between the predicted energies of these states and their experimental values but relative magnitudes of transition strengths having the same L value are not accounted for. It is probable that some of these discrepancies can be attributed to admixtures with *fp*-shell intruder states which lie outside of the model space of the theoretical calculation. The observed negative parity transitions exhaust the expected strength of single particle excitations to the $1f_{7/2}$ shell but seem to require configuration admixtures.

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*On leave from Mansoura University, Physics Dept., Faculty of Science, Mansoura, Egypt.

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