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Study of ^{32}Si Using the ^{30}Si$(t, p\gamma)$ Reaction*

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Nuclear properties of the excited states of ^{32}Si were measured using the ^{30}Si$(t, p\gamma)$ reaction at bombarding energies of $E_t = 2.7$ and 2.8 MeV. Angular correlations of γ rays were obtained using a spectrometer consisting of five NaI(Tl) counters in time coincidence with an annular particle detector positioned near 180°. Unique spin assignments for some of the excited states were obtained in addition to multipole-mixing-ratio and branching-ratio information. Nuclear lifetimes were measured using the Doppler-shift attenuation method. Some of the measured excitation energies, spins, and mean lifetimes [E_x (keV), J, and τ (psec), respectively] are as follows: 1942.5 ± 2.0, 2, 0.92 ± 0.30; 4985 ± 4, ≤ 2, ≤ 0.44; 5290 ± 3, 3, 0.27 ± 0.10; 5413 ± 3, 1, ≤ 0.074; 5956 ± 3, 2, ≤ 0.08; 6196 ± 5, 1, ≤ 0.055; 6385 ± 5, 2, ≤ 0.072. A hitherto unreported state at 4234 ± 4 keV was found to have a spin $J = 2$ and mean lifetime of $\tau = 0.38\pm 0.12$ psec. The reported spectroscopic data are compared to the predictions of recent shell-model calculations.

I. INTRODUCTION

The Nilsson strong-coupling collective model has been very successful in describing many features of the structure of nuclei in the lower portion of the *sd* shell. On the other hand, this model has enjoyed less success in describing the nuclear structure of members of the upper half of this shell. Experimental studies indicated that the level structure of these nuclei did not contain the characteristic rotational features predicted by the Nilsson model. An alternative model to explain the observed collective behavior of nuclei in this mass region, the vibrational model, has been only moderately successful.[1, 2] Glaudemans, Weichers, and Brussard[3] were the first to make extensive shell-model calculations of the structural properties of these nuclei. They included only $s_{1/2}$ and $d_{3/2}$ particles as the active members of the nuclear ensemble; the remaining nucleons were considered as constituting an inert ^{28}Si core. A substantial agreement with experiment was later realized when Wildenthal *et al.*[4] made shell-model calculations, in a vector space which includes basis states containing acitve $d_{5/2}$, $s_{1/2}$, and $d_{3/2}$ subshell nucleons, for the positive-parity states of upper-*sd*-shell nuclei. Further calculations using the above wave functions were performed by Glaudemans *et al.*[5] These treatments of the shell model resulted in excellent agreement between experimental spectroscopic data and data predicted by the above model wave functions.

One nucleus which was included in all of these model studies but of which little was empirically known is ^{32}Si. This nucleus is the $T_z = 2$ member of the mass-32 isobaric multiplet, where the lower excitations can be characteristically described by a proton closure of the $d_{5/2}$ subshell and a neutron closure of the $2s_{1/2}$ orbit, with the remaining two neutrons in the $d_{3/2}$ subshell. In order to more thoroughly test the above models an experimental investigation of the nuclear structure of ^{32}Si was initiated.

No experimental information beyond the reported excitation energies and ground-state spin and parity ($J^\pi = 0^+$) was available at the start of the experiment.[6] This situation is a reflection of the fact that the ^{30}Si (t, p) reaction ($Q_0 = +7.31$ MeV) is the most reasonable means of investigating this nucleus, and that triton beams are not commonly available. The present study used the above reaction in conjunction with particle–γ-ray angular correlation and attenuated-Doppler-shift measurements. These experimental studies have yielded previously unavailable information on spins, parities, γ-ray branching and multipole mixing ratios, and mean nuclear lifetimes. These aspects of the present report can be found in Secs. II and III, while Sec. V deals with a comparison of these experimental data and the predictions of the shell-model calculations of Wildenthal *et al.*[4]

II. Ge(Li) SPECTROMETER MEASUREMENTS

In order to better understand the decay scheme of ^{32}Si excited states beyond a point normally attainable using NaI(Tl) detectors, γ-ray spectra were obtained (in coincidence with protons at 173° ± 4°) with a 20-cm^3 Ge(Li) detector positioned alternately at 0° and 90° with respect to the beam axis. These measurements were used to determine (or put limits on) the mean lifetimes of the excited states by the Doppler-shift attenuation method, as well as to provide information concerning the excitation energies and γ-ray branching ratios associated with ^{32}Si levels. In regard to the analysis of the angular correlation data, these measurements also served to point out whether proton groups observed in the particle-γ-ray angular correlations represented one or more excited states. The $^{30}\mathrm{Si}(t,p\gamma)^{32}\mathrm{Si}$ reaction was used, with tritons of energy $E_t = 2.8$ MeV provided by the Lockheed 3.0-MV Van de Graaff accelerator. The target consisted of approximately 200 μg/cm^2 of metallic Si (enriched to 95.55% in ^{30}Si) evaporated onto 0.001-in.-thick tantalum backing, which also served as a beam dump. The data collection system consisted of conventional modular electronics and an SEL 810*A* computer interfaced to one 128- and two 8192-channel analog-to-digital convertors (ADC). This arrangement allowed a three-parameter collection of data onto magnetic tape, with simultaneous on-line and/or subsequent off-line data analysis. A typical particle spectrum collected at $173° \pm 4°$ in time coincidence with γ rays observed by the Ge(Li) detector is illustrated in Fig. 1. The particle-detector resolution was approximately 100 keV at full width at half maximum (FWHM) for the 1942-keV group.

The attenuated Doppler shifts were extracted from γ-ray spectra which were obtained at detector angles of 0° and 90° with respect to the beam axis. In order to obtain the experimental $F(\tau)$ values, the observed shifts were then compared to the expected full shift calculated from the kinematics. In the theoretical calculation of $F(\tau)$ the methods of Warburton *et al.*[7] and Blaugrund[8] were used as outlined in the paper of Jones *et al.*[9]; only those points particular to this experiment will be given below. The values for the electronic stopping parameter K_e for Si slowing down in Si and Ta were calculated, using the formulas of Lindhard and Scharff,[10] to be $K_e = 0.4$ and 1.4 keV cm$^2/\mu$g, respectively. No adjustments were made to the magnitude of these values, since according to Ormrod *et al.*[11] the experimental values should not be expected to deviate significantly from the given theoretical estimate. The nuclear stopping parameter was calculated from the equations of Lindhard *et al.*[12] as quoted by Blaugrund,[8, 13] with large-angle scattering taken into consideration according to the formalism of the latter. Included in the calculation of the theoretical $F(\tau)$ values are the necessary integrations for the combined slowing of the beam and recoil ions in the target layer and tantalum backing. Table I lists the experimental $F(\tau)$ values and the extracted lifetime or limit thereof obtained with the above analysis. It is of interest to note, despite the fact that no quantitative analysis was performed, that the effects of the lifetime of the states decaying through the 1942-keV state were observed in the shape of the line for the 1942-keV transition when collected in coincidence with protons feeding the parent state. Aside from the experimental error for the measured $F(\tau)$ value, the errors assigned to the lifetimes contain an additional 15% uncertainty due to the poor knowledge of the stopping data and other factors associated therewith. Figure 2 illustrates the photopeaks of three γ-ray transitions for which lifetimes were measured.

The excitation energies listed in Fig. 3 were values obtained from the Ge(Li)-γ-ray spectra ob-

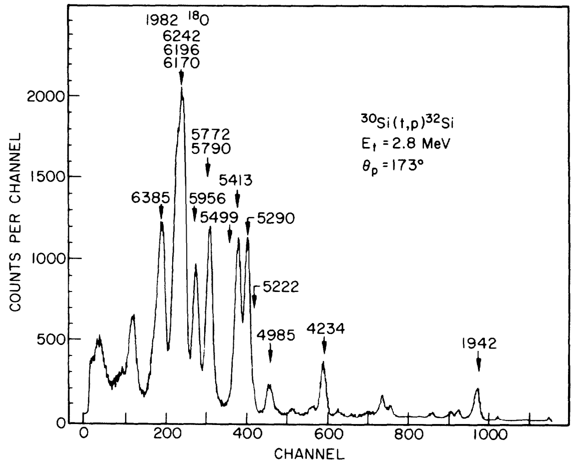

FIG. 1. The proton spectrum measured in time coincidence with all γ rays observed by the Ge(Li) detector. The weak unlabeled groups belong to the $^{28}\mathrm{Si}(t,p)^{30}\mathrm{Si}$ reaction, while the proton groups associated with the $^{30}\mathrm{Si}(t,p)^{32}\mathrm{Si}$ reaction are all labeled with the excitation energies of the corresponding states. Random coincidences have been removed from this spectrum. The particle detector resolution was approximately 100 keV at FWHM for the 1942-keV group.

TABLE I. A summary of the mean lifetime information obtained in this experiment.

State (keV)	$F(\tau)$	τ (psec)
1942	0.26 ± 0.04	0.92 ± 0.32
4234	0.49 ± 0.07	0.38 ± 0.13
4985	≥ 0.48	≤ 0.44
5290	0.61 ± 0.09	0.27 ± 0.10
5413	≥ 0.93	≤ 0.074
5772	≥ 0.74	≤ 0.2
5790	≤ 0.19	≥ 1.2
5956	≥ 0.92	≤ 0.08
6170	≥ 0.91	≤ 0.08
6196	≥ 0.95	≤ 0.055
6242	≥ 0.91	≤ 0.08
6385	≥ 0.93	≤ 0.072

tained at 90°. Because of technical difficulties related to the procurement of the calibration spectrum at the time the data were being collected, the γ-ray energy calibration had to be taken from lines contained in the coincident spectrum originating from "contaminant" reaction products such as ^{18}O and ^{30}Si. This, plus the fact that nearly all excitation energies are a result of the sum of two cascading γ-ray energies, resulted in larger error assignments than might otherwise have been given. Relative branching ratios illustrated in Fig. 3 were extracted from the coincident γ-ray spectra obtained with both the Ge(Li) and NaI(Tl) detectors.

III. PARTICLE-γ-RAY ANGULAR CORRELATIONS

The angular-correlation studies were performed at triton energies of 2.7 and 2.8 MeV. This latter energy was chosen because the yield of protons to the previously unobserved 4234-keV state was at a maximum while yet providing optimum yields to most of the other states. The target described in the previous section was also used for the angular correlation measurements. The target was positioned in the center of a table which supported five 4×4-in. NaI(Tl) detectors. The γ-ray pulses in each of these detectors were in time coincidence with proton pulses detected in an annular silicon counter subtending an angle of 173°± 4°. The proton detector was 1000 μ thick and was shielded from the scattered tritons with 10.3 mg/cm^2 of aluminum foil. The NaI(Tl) detectors were positioned at angles of (or equivalent to) 5, 35, 45, 60, and 90° with respect to the beam axis at a distance of 8 in. from the target beam spot. A detailed description of the electronic configuration can be found in a report by Chalmers.[14] Preliminary isotropy checks of the five-counter array were made by observing the γ-ray decay of known spin $J = 0$ or $\frac{1}{2}$ states in a number of *sd*-shell nuclei. Subsequent on-line checks were made during the experiment by observing β-γ coincidences from a ^{228}Th source mounted on a plastic scintillator positioned equidistant from the NaI detectors. These monitoring data were stored on tape, with appropriate identification flags, and served as a dead-time monitor for each of the five counters. The usual corrections for dead-time and instrumental anisotropy were found to be negligible. The correlation data were analyzed by a least-squares fitting (and χ^2 analysis in terms of initial spins) of the experimental points to the theoretical angular distributions calculated according to the formulas of the "method-II geometry" of Litherland and Ferguson.[15] A least-squares fit to an expansion of even-order

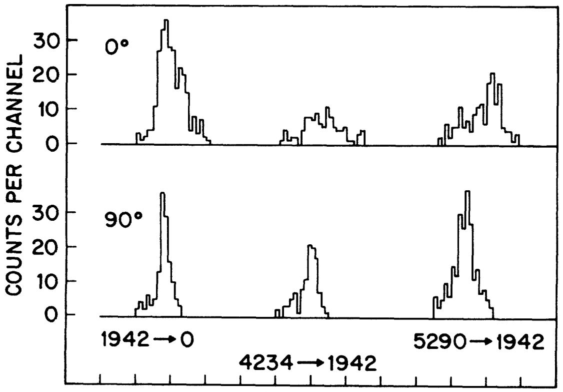

FIG. 2. The photopeaks of the indicated transitions as observed by the 20-cm^3 Ge(Li) detector in coincidence with protons detected at 173°± 4°. The energy dispersion is 2.5548 keV per channel.

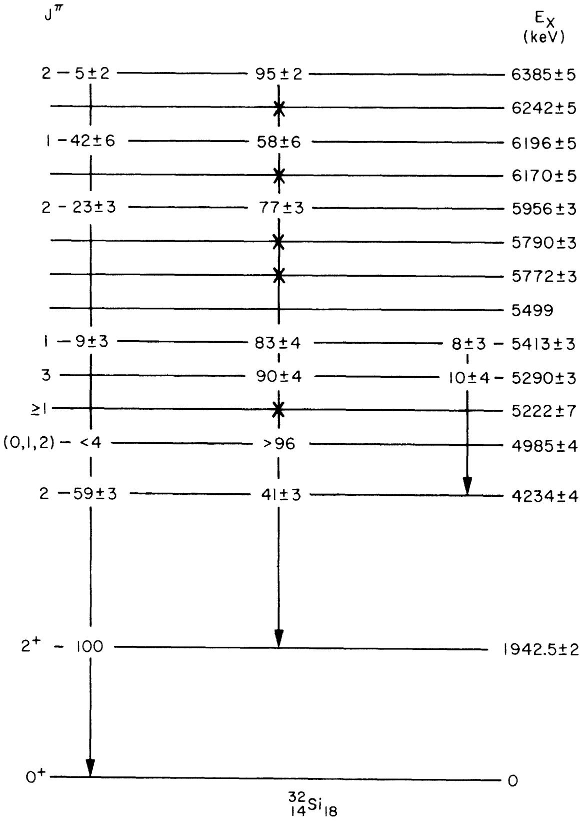

FIG. 3. A summary of the spectroscopic information obtained in the present experiment for the excited states of ^{32}Si. The 5499-keV state was not observed in this experiment. The large × represents those transitions which were observed experimentally, but to which no corresponding branching ratio could be assigned.

Legendre polynomials was also made, and the resulting coefficients appear in Table II. In the collinear geometry employed, γ rays from only $m = 0, \pm 1$ substates are observed.[15] To account for the finite solid angle of the particle detector it was assumed in the analysis that the relative population of the $m = 0, \pm 2$ substates was such that $P(2)/P(0) \leq 0.05$. The finite solid angle effect was in most cases small, and the results are incorporated into the χ^2 curves illustrated. Because of the magnitudes of the measured lifetimes listed in Table I, it is assumed that octupole radiation need not be considered in the analysis. Wherever possible χ^2 analysis for a given state included data of all γ rays whose angular correlations are dependent on the alignment of the initial state. Table III lists the measured multipole mixing ratios obtained from the above analyses.

IV. SYNTHESIS OF RESULTS

A. 1942-keV State

The angular correlation data obtained for the $1942 \rightarrow 0$-keV transition displayed a very large $P_4(\cos\theta)$ term, as is evident from the coefficients listed in Table II. This immediately implies a spin assignment of $J \geq 2$ for this state. The subsequent least-squares analysis corroborated this by virtue of the resulting χ^2 values of 198, 2, and 195 for respective spin assignments of $J = 1$, 2, and 3. For a spin assignment of $J = 2$, the measured lifetime of $\tau = 0.92 \pm 0.3$ psec implies an $E2$ strength of 5.1 ± 1.5 Weisskopf units (W.u.) and an $M2$ strength of ~163 W.u. Because this latter value is atypical of expected $M2$ strengths, it can be assumed that the parity of this state is positive. This is not totally unexpected, since the first excited state of most even-even members of the upper portion of the s-d shell have a $J^\pi = 2^+$ assignment.

TABLE II. The Legendre polynomial expansion coefficients for the angular correlations obtained at a beam energy of $E_t = 2.8$ MeV. The analyses include the appropriate correction for the solid angle of the γ-ray detector.

State (keV)	E_i (keV)	E_f (keV)	a_2/a_0	a_4/a_0
1942	1942	0	0.67 ± 0.14	-1.42 ± 0.15
4234	4234	1942	-0.10 ± 0.11	-0.28 ± 0.11
	1942	0	0.00 ± 0.10	$+0.40 \pm 0.10$
	4234	0	0.81 ± 0.10	-1.80 ± 0.10
4985	4985	1942	0.02 ± 0.06	0.08 ± 0.06
	1942	0	0.06 ± 0.04	-0.06 ± 0.04
5222	5222	1942	0.26 ± 0.04	0.11 ± 0.05
	1942	0	0.28 ± 0.06	0.08 ± 0.07
5290	5290	1942	-0.18 ± 0.01	-0.03 ± 0.01
	1942	0	0.52 ± 0.07	-0.29 ± 0.06
5413	5413	1942	0.10 ± 0.07	-0.11 ± 0.07
	1942	0	0.29 ± 0.04	$+0.01 \pm 0.04$
	5413	0	-0.21 ± 0.08	-0.01 ± 0.08
5956	5956	1942	0.44 ± 0.03	-0.06 ± 0.03
	1942	0	0.37 ± 0.04	0.60 ± 0.04
	5956	0	0.55 ± 0.04	-1.13 ± 0.04
6196	6196	0	-0.31 ± 0.03	-0.01 ± 0.03
6385	6385	1942	0.46 ± 0.01	-0.01 ± 0.01
	1942	0	0.35 ± 0.06	0.46 ± 0.07

B. 4234-keV State

The existence of the 4234-keV state had not been experimentally observed prior to this study. For this reason a beam energy was chosen ($E_t = 2.8$ MeV) for the angular correlation studies at which the proton yield to this state was at a maximum. Figure 4(a) illustrates the γ-ray spectrum obtained in the NaI(Tl) spectrometer at $\theta_\gamma = 45°$. Ge(Li) γ-ray spectra taken in coincidence with the corresponding particle group confirmed the

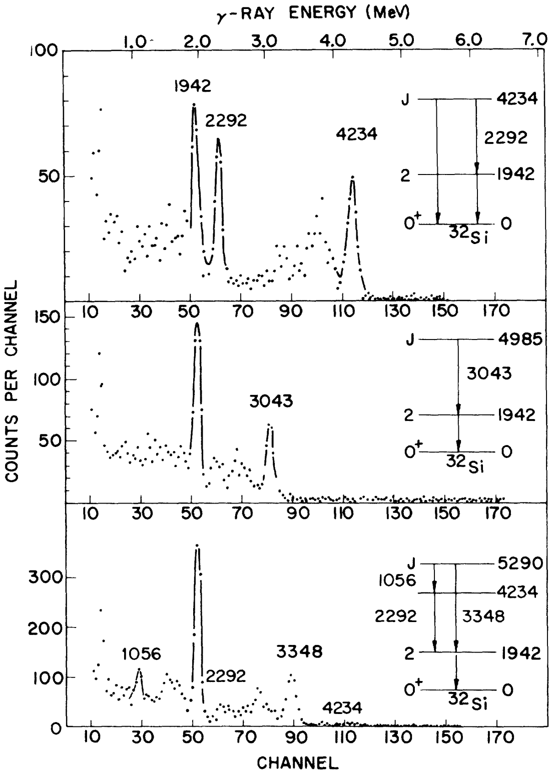

FIG. 4. The γ-ray spectra obtained at $\theta_\gamma = 45°$ in time coincidence with proton groups leading to three of the excited states in ^{32}Si. The corresponding protons were detected at 173° ± 4° to the beam direction. Random coincidences have been subtracted from these spectra. The photopeaks of the cascading γ rays are labeled by their associated energy in keV.

existence of γ rays resulting from a crossover transition and a cascade through the 1942-keV state of ^{32}Si. Angular correlations for all three γ rays associated with the deexcitation of this state were reduced from the data and are illustrated in Fig. 5. The least-squares analysis of the ground-state transition alone results in a unique spin assignment of $J=2$; all other spins are eliminated at less than the 0.1% confidence limit. In order to fix a value for the electromagnetic mixing ratio of the 4234 → 1942-keV transition a subsequent χ^2 analysis involving all three transitions was performed; this is illustrated in Fig. 5. Here again all spin assignments but $J=2$ are rejected at the prescribed confidence limit. Calculations involving the measured lifetime, branching, and mixing ratios indicate that the 4234 → 0-keV transition has an $E2$ or $M2$ strength of 0.15 ± 1.5 W.u. or 5.0 ± 1.5 W.u., respectively, while the corresponding strength for the 4234 → 1942-keV transition is 0.92 ± 0.27 W.u. or 29 ± 10 W.u. Positive parity is thus not required on the basis of the above evidence alone, although the second excited states of even-even nuclei in this region of the s-d shell consistently have positive-parity assignments.

C. 4985-keV State

Figure 4 illustrates the γ-ray spectrum observed in coincidence with the protons feeding the 4985-keV state. As can be seen from the coefficients listed in Table II, the angular correlations of the cascading γ rays from this state were essentially isotropic. This was true also of the correlations obtained at a beam energy of $E_t = 2.7$ MeV. The subsequent χ^2 analysis indicated good fits for $J=0$, 1, and 2; the associated mixing ratios are given in Table III. The complete isotropy of the measured correlations and the lack of a measurable ground-state transition lead to the speculation that this state may be the expected second $J^\pi = 0^+$ state in ^{32}Si. In regard to the lifetime studies, the statistical accuracy of the data collected in the Ge(Li) studies of Sec. II for this state was poor, and it was not possible to extract accurate Doppler-shift information. A definite shift was observed, however, and it was possible to set a lifetime limit of $\tau \leq 0.44$ psec. Assuming a pure $E2$ transition to the first excited state, this lifetime would correspond to a transition strength of ≥ 1.17 W.u.

TABLE III. Multipole mixing ratios for various γ-ray transitions in ^{32}Si as observed in the present studies. The phase convention is that of Ref. 15.

E_i (keV)	E_f (keV)	J_i	J_f	Multipole mixing ratio [a]
4234	1942	2	2	$+0.84 \pm 0.44$
4985	1942	1	2	Undetermined
4985	1942	2	2	$+0.3 \pm 0.16$
5290	1942	3	2	-0.07 ± 0.04
5413	1942	1	2	0.13 ± 0.33
5956	1942	2	2	$+0.01 \pm 0.06$
6385	1942	2	2	-0.04 ± 0.04

[a] The mixing ratio is defined in terms of quadrupole and dipole mixing only.

D. 5222-keV State

This state was very weakly populated at the beam energies used in the present investigation. The Ge(Li) spectra indicated a transition to the first excited state from a level at 5222 ± 7 keV; it was impossible with the available statistical accuracy to ascertain whether or not there was a ground-state transition from this state. By investigating

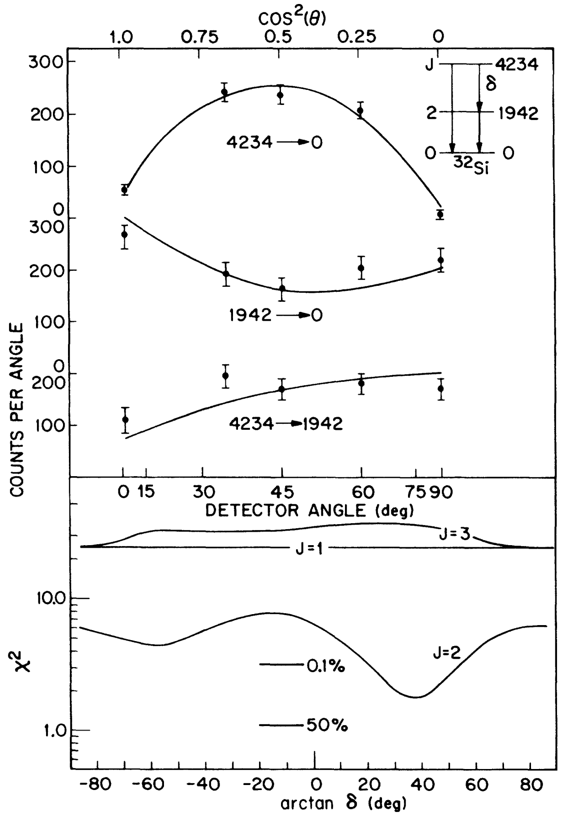

FIG. 5. The angular correlations for the γ rays cascading from the 4234-keV state, and the associated χ^2 analyses. The solid lines through the data points represent the best fit for the spin $J=2$ and have been corrected for the solid angle of the γ-ray detectors.

the γ-ray spectra in coincidence with various portions of the composite particle group, it was possible to resolve the spectra of γ rays from the 5222- and 5290-keV states. A definite difference in anisotropy was observed for the γ-ray angular correlations from the two states (see Table II). The subsequent χ^2 analysis of these data limited the spin of the 5222-keV state to $J \geq 1$.

E. 5290-keV State

Angular correlations for this state were extracted from spectra obtained in coincidence with protons in a narrow region of energy situated in the center of the 5290-keV group (see Fig. 4). The possibility of contributions by transitions from states nearby, which could not be resolved in the NaI(Tl) spectrometer and particle counter, consequently was eliminated. There was no observable transition to the ground state, but two cascades were noted: one through the 1942-keV state and one through the 4234-keV state. The latter cascade was too weak to allow reliable angular correlations to be extracted. The angular correlations and the associated χ^2 analysis for the former cascade are illustrated in Fig. 6. This analysis indicates that only a spin assignment of $J = 3$ gives an acceptable fit for the angular correlation data. This analysis neglects the fact that the 1942-keV transition has a 4% contribution from the 5290 → 4234→ 1942-keV cascade. It is expected that this will not influence significantly the resulting value for the multipole mixing ratio for the 5290 → 1942-keV transition. Using the measured lifetime of $\tau = 0.27 \pm 0.1$ psec and the mixing and branching ratios listed in Table III and Fig. 3, the $E1$ and $M2$ strengths for the transition from this state to the first excited state were calculated to be 0.89×10^{-4} W.u. and 0.20 W.u., respectively; similarly, the calculated $M1$ and $E2$ strengths are 0.28×10^{-2} W.u. and 5×10^{-3} W.u., respectively. These strengths for both parity assignments are not atypical of the respective transitions. Further discussion regarding the parity of this state can be found in the final section of this paper.

F. 5413-keV State

The proton group labeled 5413 keV in Fig. 1 was found from the Ge(Li) studies of Sec. II to corre-

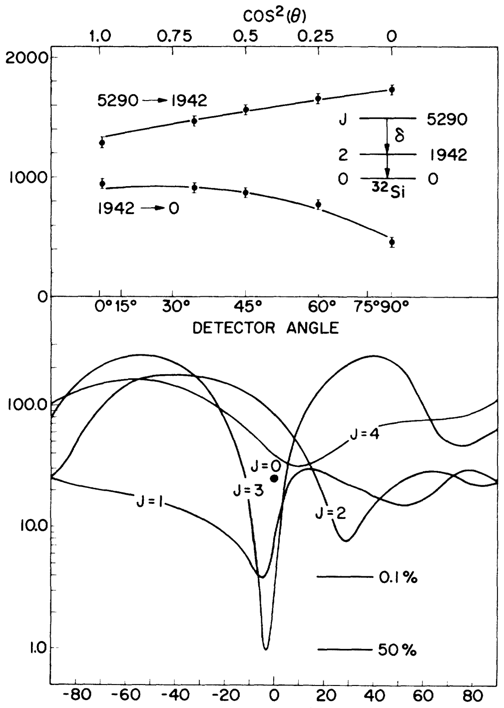

FIG. 6. The angular correlations for the γ rays cascading from the 5290-keV state, and the associated χ^2 analyses. The solid lines through the data points represent the best fit for the spin $J = 3$ and have been corrected for the solid angle of the γ-ray detectors.

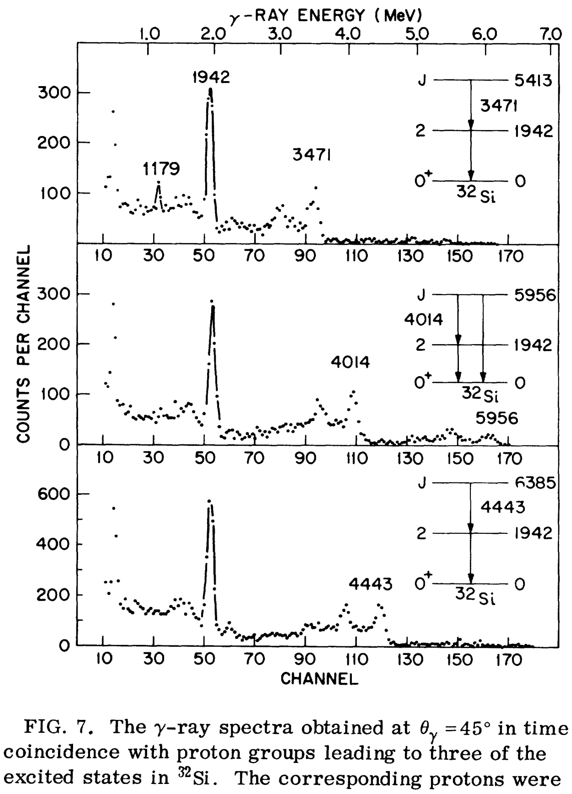

FIG. 7. The γ-ray spectra obtained at $\theta_\gamma = 45°$ in time coincidence with proton groups leading to three of the excited states in ^{32}Si. The corresponding protons were detected at 173°± 4° to the beam direction. Random coincidences have been subtracted from these spectra. The photopeaks of the cascading γ rays are labeled by their associated energy in keV. The 1179-keV line results from a transition between the 5413- and 4234-keV states.

spond to a single state of that energy. The group corresponding to the 5499-keV state was not observed in the experiment, and the excitation energy is listed in this paper as given in Ref. 5. The γ-ray spectrum observed in coincidence with the protons leading to the 5413-keV state is illustrated in Fig. 7. It was possible to obtain reliable angular correlation data only for the 5413 → 1942 → 0-keV cascade, and this is illustrated in Fig. 8 along with the associated χ^2 analysis. It is clearly seen from this illustration that only a spin $J=1$ is acceptable for the 5413-keV state. The measured lifetime limit of $\tau \leq 0.074$ psec and the multipole mixing and branching ratios listed in Table III and Fig. 3 give limits on the transition strengths typical of transitions in the s-d shell.

G. 5499-, 5772-, and 5790-keV States

As was pointed out in the previous paragraph, the 5499-keV state was not observed in this experiment. The 5772- and 5790-keV states were observed in the Ge(Li) spectra to have comparable intensities in the yield of the corresponding proton group illustrated in Fig. 1. The γ-ray spectrum obtained in coincidence with this proton group indicated no observable ground-state transition for either of the two states represented. Both states have their main decay routes through the 1942-keV state. These transitions were not resolved in energy by the NaI(Tl) detectors, and consequently the composite angular correlation data (which indicated only slight anisotropies) were useless in determining the spins of either state. The Ge(Li) coincident spectra indicated that the 5772 → 1942-keV transition had a large Doppler shift, while the 5790 → 1942-keV transition had no significant shift. The two lines overlapped at 0°; hence only limits could be placed on their respective shifts as indicated in Table I.

H. 5956-keV State

It was ascertained, from the Ge(Li) spectrum taken in coincidence with the group indicated as

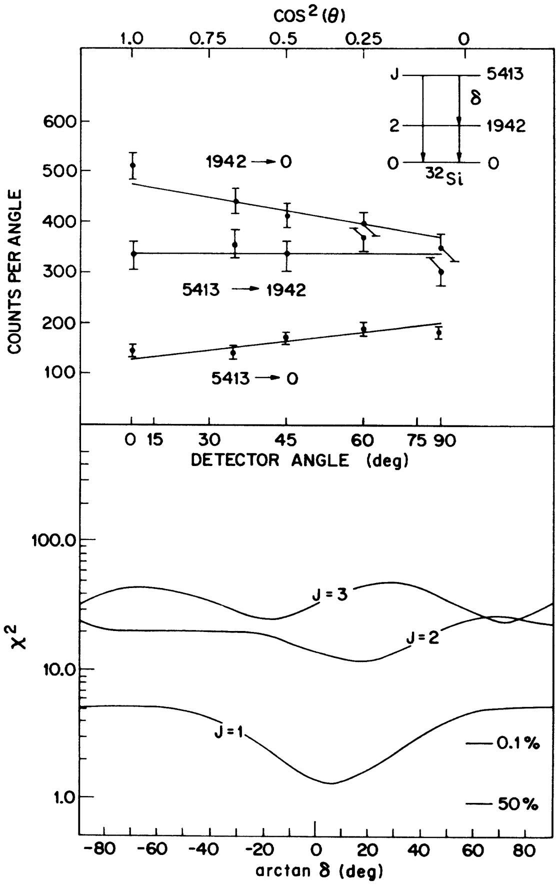

FIG. 8. The angular correlations for the γ rays cascading from the 5413-keV state, and the associated χ^2 analyses. The solid lines through the data points represent the best fit for the spin $J=2$ and have been corrected for the solid angle of the γ-ray detectors.

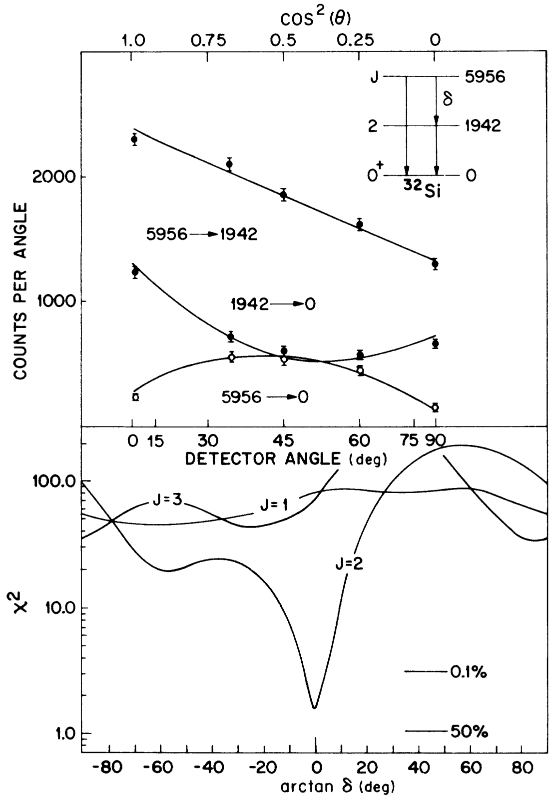

FIG. 9. The angular correlations for the γ rays cascading from the 5956-keV state, and the associated χ^2 analyses. The solid lines through the data points represent the best fit for the spin $J=2$ and have been corrected for the solid angle of the γ-ray detectors.

5956 keV in Fig. 1, that this was a proton group representing a single state of that energy. The NaI(Tl) γ-ray spectrum taken in coincidence with this group is illustrated in Fig. 7. It was possible to obtain the angular correlations for all three of the coincident γ rays shown. The analysis of the angular correlation data for the 5956 → 0-keV transition alone resulted in the exclusion of all spins but $J = 2$. Figure 9 illustrates the angular correlation data for all three γ rays as well as the associated χ^2 analysis of the combined data. It is clearly seen that only a spin $J = 2$ can generate curves which fit the combined data. A limit of $\tau \leq 0.08$ psec was placed on the lifetime, but no conclusion can be drawn from the transition strengths in regard to the parity of the 5956-keV state.

I. 6170-, 6196-, and 6242-keV States

Figure 1 illustrates a single proton group as representing the 6170-, 6196-, and 6242-keV ^{32}Si excited states as well as the "contaminant" 1982-keV ^{18}O state. The γ-ray spectra obtained in coincidence with this group indicated that of the three ^{32}Si states only the 6196-keV state had an observably significant ground-state transition. The other two states had their main decay route through the 1942-keV state. The analysis of the angular correlation data for the 6196 → 0-keV transition resulted in a unique spin assignment of $J = 1$ ($\chi^2 = 0.75$). The other spin alternatives had χ^2 values ≥ 150. No conclusions concerning the parity of these states can be made from the lifetimes listed in Table I.

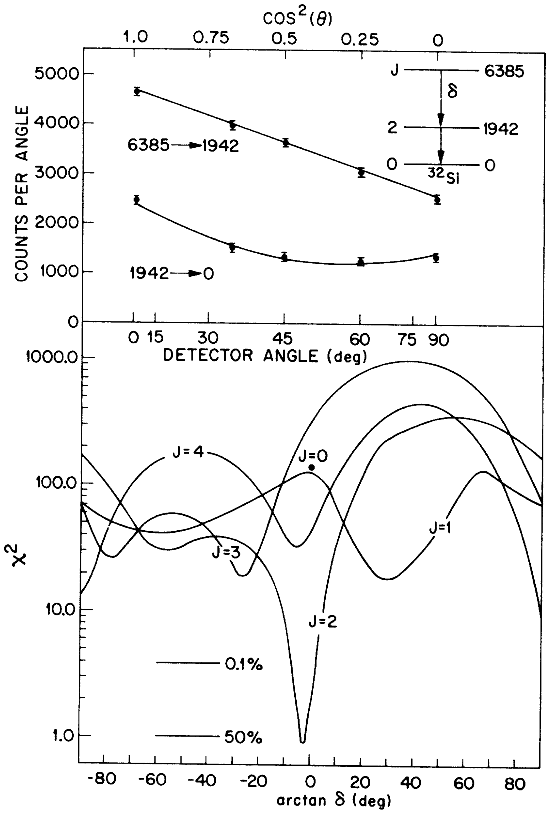

FIG. 10. The angular correlations for the γ rays cascading from the 6385-keV state, and the associated χ^2 analyses. The solid lines through the data points represent the best fit for the spin $J = 2$ and have been corrected for the solid angle of the γ-ray detectors.

J. 6385-keV State

The Ge(Li) studies of Sec. II indicate that the observed proton group of Fig. 1 corresponds to a single state of 6385-keV excitation energy. The γ-ray spectrum obtained in coincidence with protons leading to this state is illustrated in Fig. 7. Angular correlation data for the cascade through the first excited state were obtained, and are illustrated in Fig. 10 along with the associated χ^2 analysis of the combined data. It is evident from the analysis presented in this figure that only a spin $J = 2$ is an acceptable spin assignment for the 6385-keV state. No conclusion can be drawn concerning the parity of this state from the measured limit of $\tau \leq 0.072$ psec.

V. DISCUSSION

A synthesis of the experimental results obtained for the level structure of ^{32}Si is illustrated in Fig. 3. As is evident, there are enough significant data to allow a meaningful comparison to be made with the predictions of the shell model. The most recent calculations of Wildenthal *et al.*[4] will be used for this comparison. In these calculations (which cover masses 30–35), it is assumed that the 1s and 1p shells are filled at all times and that never more than two particles are promoted from the $d_{5/2}$ shell to higher excitations. The remaining nucleons are in various excitations within the $2s_{1/2}$ and $1d_{3/2}$ subshells. One of the Hamiltonians used was based on a modified surface δ interaction (MSDI) and involves four interaction parameters and three single-particle energies to specify the complete effective Hamiltonian. These parameters were optimized by adjusting them in a least-squares fit to 66 pieces of experimental data pertaining to levels of nuclei in this mass region. An alternative effective Hamiltonian (FPSDI) used was derived by keeping the matirx elements involving the $d_{5/2}$ orbits fixed as obtained from a MSDI calculation and adjusting the remaining 15 matrix elements as well as the original 7 parameters to best represent the 66 pieces of experimental data. Fig-

TABLE IV. A comparison of some of the experimental results with the predictions of the shell model. The tabulated theoretical results are those of Wildenthal, McGrory, Halbert, and Graber (see Refs. 4 and 16).

$J_i \to J_f$	$E_i \to E_f$ (keV)		$B(M1)$ (μ_N^2)		$B(E2)$ e^2 fm^4	
($T=2$)	Experiment	Theory	Experiment	Theory	Experiment	Theory
2 → 0	1942 → 0	1860 → 0	···	···	30 ± 11	35.7
2 → 0	4234 → 0	4210 → 0	···	···	0.89 ± 0.35	1.27
2 → 2	4234 → 1942	4210 → 1860	$(2.9 \pm 1.1) \times 10^{-3}$	2.6×10^{-3}	7.48 ± 6.17	8.92
0 → 2	4985 → 1942	4300 → 0	···	···	≥6.95	26

ure 11 illustrates the level scheme generated by both Hamiltonians for the positive-parity states only. Since the FPSDI Hamiltonian appears to give a slightly better over-all correspondence to the experimental scheme, it is this Hamiltonian which is used in generating transition rates for subsequent comparisons. In calculating the $E2$ transition rates, effective nucleon charges of $e_p = 1.5e$ and $e_n = 0.5e$ are used, while for the $M1$ transition rates free-nucleon g factors of $g_p = 5.58$ and $g_n = -3.82$ were used. (For a more detailed description of the calculations, the reader is referred to the original article.[4])

Table IV lists some of the experimental and theoretical[4, 16] spectroscopic properties associated with the first three excited states and their respective electromagnetic transitions. It is assumed that the observed states listed can all be identified as positive-parity, $T=2$ states. The remaining states are not considered here since their identification cannot be made with any degree of confidence. The theoretical $B(M1)$ and $B(E2)$ values were calculated using the wave functions as described above. The experimental $B(M1)$ and $B(E2)$ values were taken from the present data according to Eqs. (7) and (10) of Ref. 17. There

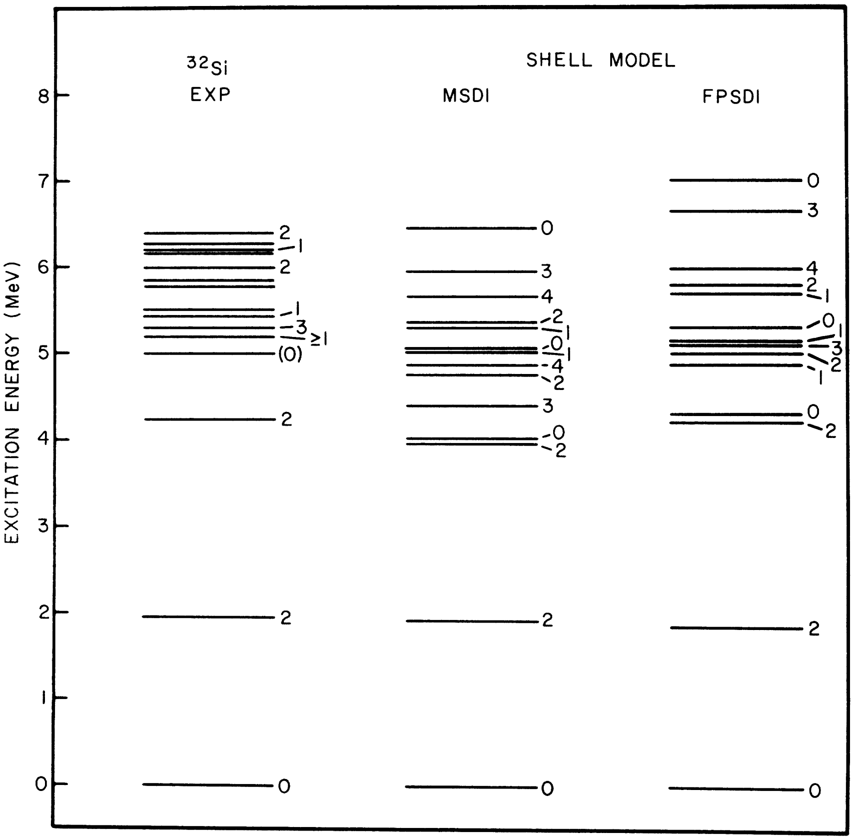

FIG. 11. A comparison of the experimental level scheme of ^{32}Si with the predictions of the shell-model calculations of Ref. 4.

appears to be very good agreement between theory and experiment for the cases tabulated. It is impressive that such good agreement should be obtained in both transition strengths and level positions, since the parameters used in deriving the wave functions for this nucleus were taken from the general properties of other nuclei in this mass region.

Although the parity of the $J=3$, 5290-keV state has not been measured, some remarks concerning this state can be made in regard to the transition rates to the 1942-keV level. The first $J^\pi=3^+$ state in the FPSDI calculations has $B(M1)$ and $B(E2)$ values of $0.239\mu_N{}^2$ and 0.195 $e^2\text{fm}^4$, respectively, for the decay to the first excited state. What is experimentally found are the values $(0.56\pm0.2)\times10^{-2}\mu_N{}^2$ and 0.35 ± 0.028 $e^2\text{fm}^4$, respectively. It would appear that, in view of such good agreement between theory and experiment for the lower states and the large disagreement here, this state might more likely be a $J^\pi=3^-$, $f_{7/2}$ excitation. The systematics observed in the position of the lowest excited $J^\pi=3^-$ state for other s-d shell nuclei in this mass region would suggest such a state to be in this region of excitation. The necessary $E1$ inhibition and $M2$ strength noted in Sec. IV E would not rule out such an interpretation.

It should be pointed out again that the spin of the 4985-keV state, and hence the transition rate comparison listed for this state in Table IV, are tentative assignments only in that this state has not been uniquely assigned a spin value. It is hoped that further studies in the nature of direct-reaction (t, p) angular distributions will clarify the present situation.

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