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Proton Capture Gamma Rays from the Reaction $P^{31}(p,\gamma)S^{32}$ Leading to the Ground and First Excited States of S^{32}

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Resonances in the reaction $P^{31}(p,\gamma)S^{32}$ which show transitions to the ground or first excited state of S^{32} have been studied for proton energies between 0.68 and 2.35 Mev. Angular distributions have been measured at resonances at 0.816, 0.825, 1.117, 1.146, 1.248, 1.892, 1.985, 2.027, 2.120, 2.320, and 2.340 Mev. These distributions along with the $P^{31}(p,\alpha_0)Si^{28}$ results enabled assignments of $1-$ to be made for the resonances at 1.892, 2.027, and 2.120 Mev, of $1\pm$ for those at 0.825, 1.117, 1.985, 2.320, and 2.340 Mev, and of $2\pm$ to that at 1.248 Mev. Partial widths for γ_0 and γ_1 were also measured and are compared with theory. Analysis of the angular distributions at one resonance suggests that the spin of the first excited state of S^{32} at 2.25 Mev is $2+$. The reduced proton widths for the three resonances with $J=1-$ together amount to 60 percent of the single-particle width.

INTRODUCTION

THE yield of gamma rays from phosphorus bombarded with protons has been studied by a number of workers. Grove and Cooper,[1] using a single Geiger-Muller counter and a Zn_3P_2 target of 10 kev thickness at 1.3 Mev, found 16 resonances in the range of proton energies from 0.4 to 1.65 Mev. Smith, Cooper, and Harris[2] have measured the gamma-ray spectra at five of these resonances using a scintillation counter. Kern and Cochran[3] have reported spectra observed in a thick target using a scintillation counter. Olness and Lewis[4] have also reported some results for proton energies from 1.4 to 3.36 Mev including evidence for the reactions $P^{31}(p,p'\gamma)$ and $P^{31}(p,\alpha\gamma)$ at proton energies above 2.3 Mev.

The present paper describes measurements of the yield, angular distribution, and partial widths of proton capture gamma rays leading to the ground and first excited states of S^{32} at those resonances which showed these gamma rays between proton energies of 0.68 and 2.35 Mev. Some of these results have been reported previously.[5,6] From these measurements it is possible to make definite spin assignments to several of the capturing states, to draw some conclusions about the first excited state of S^{32}, and to relate some of the measured widths to theoretical $E1$ widths. For some of the resonances the total width could be measured, and this is compared to the theoretical single-particle width. A comparison between the measured angular distributions and those predicted by jj and ls coupling is given.

EXPERIMENTAL ARRANGEMENT

The Chalk River electrostatic generator provided the source of bombarding protons. These protons were analyzed in energy by a 90° magnet whose field was held constant by a proton resonance fluxmeter. A pair of tantalum plates forming a horizontal slit at the exit of this magnet provided a signal to control a corona load, and the proton energy was held constant to about 0.1 percent. The protons travelled along a 15-foot section of evacuated tubing terminated by a hollow brass cylinder with $\frac{1}{16}$-inch thick walls containing the target. The arrangement, shown schematically in Fig. 1, has been described previously.[7] A $\frac{1}{8}$-inch aperture in a 20-mil tantalum disk located about eight feet from the

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[1] G. R. Grove and J. N. Cooper, Phys. Rev. **82**, 505 (1951).

[2] Smith, Cooper, and Harris, Phys. Rev. **94**, 749(A) (1954); J. A. Smith, Ohio State University thesis, 1953 (unpublished).

[3] B. D. Kern and L. W. Cochran, Bull. Am. Phys. Soc. **30**, No. 3, 45 (1955).

[4] J. W. Olness and H. W. Lewis, Bull. Am. Phys. Soc. **30**, No. 3, 54 (1955).

[5] H. E. Gove and E. B. Paul, Phys. Rev. **92**, 852(A) (1953).

[6] Gove, Paul, Litherland, and Bartholomew, Phys. Rev. **95**, 650(A) (1954).

[7] H. E. Gove and E. B. Paul, Phys. Rev. **97**, 104 (1955).

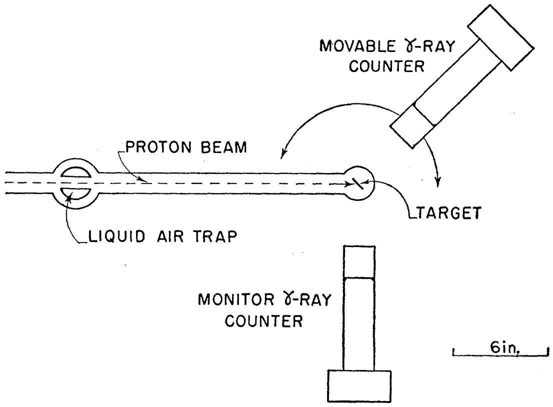

FIG. 1. Schematic diagram of experimental equipment showing the two NaI(Tl) gamma-ray counters in position for measuring angular distributions. The crystal size shown here is 2 in. diameter by 2 in. long.

target defined the beam to a spot about $\frac{1}{4}$-inch diameter. Beam currents from 5 to 20 μa were used. The targets were made by evaporating Zn_3P_2 on 20-mil tantalum backings to a thickness of about 700 ev at 1.25 Mev for the yield measurements and about 10 kev for the angular distributions. Most of the measurements were made with two-inch diameter by two-inch long NaI(Tl) crystals optically coupled to Dumont 6292 photomultipliers, although some of the later measurements employed five-inch diameter by four-inch long NaI(Tl) crystals coupled to Dumont K1198 photomultipliers. A preamplifier located at the photomultiplier drove a long cable to a linear amplifier. The output from the latter could be displayed on a 30-channel analyzer. Two such counters could be mounted on arms pivoted in the center of a four-foot-square steel-topped table arranged so that it could be moved vertically and horizontally to line a pointer located at the center of rotation of the counters with a conical hole in the target support. The counters could be rotated on this table from 0° to about 150° with respect to the proton beam.

EXPERIMENTAL PROCEDURE

For yield measurements a counter was set at 90° to the beam at a mean distance of three inches to the target center. The yield as a function of proton energy was then measured, recording only pulses corresponding to gamma-ray transitions to the ground and first excited state at 2.25 Mev[8] in S^{32}. When a resonance was located in this way the gamma-ray spectrum was recorded in the 30-channel pulse analyzer at the peak of the resonance. In those cases where the ground-state gamma ray was present another yield curve was run over the resonance with the bias set so that only this gamma ray was recorded in order to confirm that it was resonant. The target thickness was measured in an additional experiment in which the energy loss in the target was determined by comparing the step in a thick-target yield curve (20–30 kev) with the area under the thin-target yield[9] at the well-isolated resonance at 1.248 Mev. The target thickness was found to be 700 ev at this resonance. The number of gamma rays leading to the ground or first excited state per proton was then computed in the usual way,[9] by assuming that the flat portion of the Compton spectrum below the pair annihilation peaks and Compton edge could be extrapolated to zero pulse height.[7] This procedure was checked using the $F^{19}(p,\alpha\gamma)$ reaction and was found to give agreement within 10 percent.

For the angular distribution measurements one counter was located at a mean distance of five inches from the target center, subtending a solid angle of about one percent of the sphere, and could be rotated with respect to the beam between 0° and 150°. An identical monitor counter was fixed on the other side of the beam at 90° at a mean distance of four inches from the target. The targets used for angular distributions were about 10 kev thick. The ratio of the counts recorded in the movable counter to those recorded simultaneously in the fixed counter was measured. The angular distribution so obtained was shown to be insensitive to small variations in target thickness and beam intensity. A correction of about 10 percent was applied to relate values of this ratio measured at angles greater than 90° to those measured at less than 90° to take account of gamma-ray absorption in the 0.020-inch thick tantalum backing of the target.

The results were analyzed on the Ferranti computer at the University of Toronto by the method of least squares[10] in a Legendre polynomial expansion up to

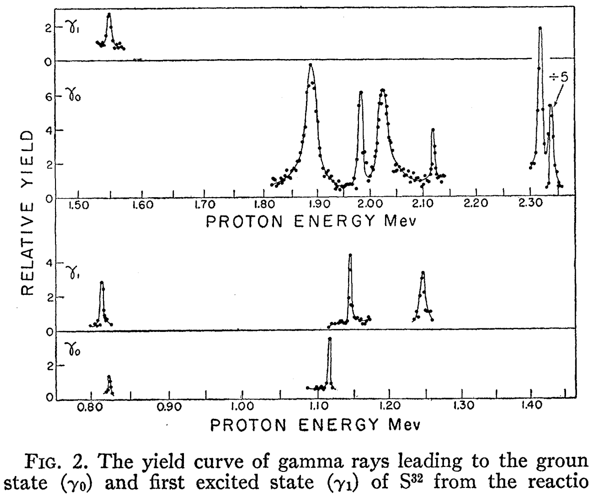

FIG. 2. The yield curve of gamma rays leading to the ground state (γ_0) and first excited state (γ_1) of S^{32} from the reaction $P^{31}(p,\gamma)S^{32}$.

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[8] Arthur, Allen, Bender, Hausman, and McDole, Phys. Rev. **88**, 1291 (1952).

[9] Fowler, Lauritsen, and Lauritsen, Revs. Modern Phys. **20**, 236 (1948).

[10] M. E. Rose, Phys. Rev. **91**, 610 (1953).

and including P_4 with standard deviations for each coefficient.

EXPERIMENTAL RESULTS

The yield curve for gamma rays from proton capture in P^{31} leading to either the ground or the first excited state of S^{32} measured at 90° to the beam is shown in Fig. 2. The curve shows 12 resonances, eight of which resonate predominantly for γ_0 and four predominantly for γ_1. It was shown that of these latter four, those at 0.816, 1.146, and 1.549 Mev were not resonant for γ_0 while that at 1.248 Mev was weakly resonant for γ_0. This latter weak resonance is not shown on the yield curve for γ_0. There are also a large number of resonances in this reaction which do not resonante for either the ground state (γ_0) or the first excited state (γ_1) transition with any appreciable intensity and which were not studied in the present work. The gamma-ray spectrum has been measured using the five-by-four-inch crystal at several resonances. Representative spectra at the resonances at 1.248, 1.892, and 1.985 Mev are shown in Fig. 3.

The yield curve for the $P^{31}(p,\alpha)Si^{28}$ reaction leading to the ground state of Si^{28} has been measured[11] in this laboratory using a 180° double-focusing magnetic spectrometer at 90° to the beam. The $P^{31}(p,\gamma)$ yield was measured simultaneously for comparison. Referring to the yield curve of Fig. 2, ground-state alpha-particle resonances were observed to coincide with the gamma-ray resonances at 1.892, 2.027, and 2.120 Mev. No ground-state alpha resonance was observed at the other resonances shown. It is interesting to note that in the region near the gamma-ray resonance at 1.985 Mev, two ground-state alpha resonances were observed at about 1.98 and 1.99 Mev respectively, these positions being distinctly different from that of the gamma-ray resonance.

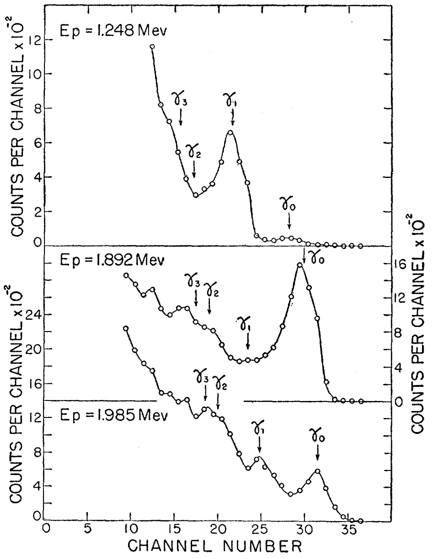

FIG. 3. Typical spectra of the high-energy gamma rays from the reaction $P^{31}(p,\gamma)S^{32}$ as measured by a large (5 in. diameter by 4 in. long) NaI(Tl) crystal at the resonances at 1.248, 1.892, and 1.985 Mev.

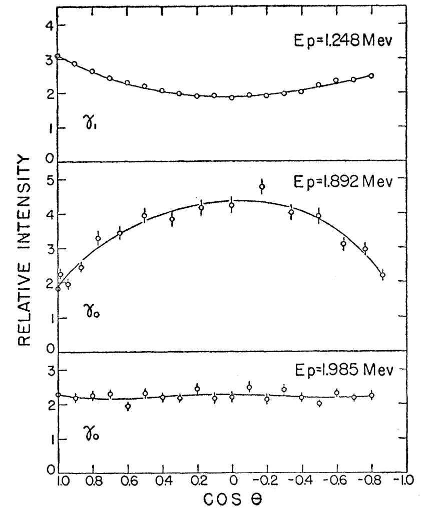

FIG. 4. Examples of the angular distributions of gamma rays from the reaction $P^{31}(p,\gamma)S^{32}$ at the resonances at 1.248 (γ_1), 1.892 (γ_0), and 1.985 (γ_0) Mev.

Angular distributions of either γ_0 or γ_1 have been measured at all of the resonances shown in the yield curve of Fig. 2 excepting that at 1.549 Mev. The resonance at 1.248 Mev shows a weak γ_0, and an attempt was made to measure its angular distribution. The problem of background correction was such that only a very rough estimate of the coefficient of P_2 could be made. Examples of the angular distributions are shown in Fig. 4, where the curves for the first excited-state transition at the 1.248-Mev resonance and the ground-state transition at the 1.892- and 1.985-Mev resonances are given. Values of the coefficients and their standard deviations of the Legendre polynomial expansions which were least squares fitted to the experimental points are listed in Table I for ground-state gamma transitions and in Table II for first excited-state transitions.

Smith, Cooper, and Harris[2] have examined the gamma-ray spectrum at five resonances in the $P^{31}(p,\gamma)S^{32}$ reaction. Four of these occur in the proton energy region covered in the present work. The resonances they observe at 0.820, 1.140, and 1.170 Mev correspond respectively to the resonances reported in this paper at 0.816, 1.117, and 1.146 Mev. The resonance they observed at 0.900 Mev is reported to show a gamma-ray transition to the first excited state of S^{32}, but none to the ground state. A resonance in this region observed in the present work failed to show an appreciable transition to either the ground or first excited state, and hence is not included in this survey. A possible

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[11] Clarke, Almqvist, and Paul, Bull. Am. Phys. Soc. **30**, No. 3, 54 (1955).

TABLE I. The coefficients of a Legendre polynomial series $W(\theta) = P_0 + (a_1/a_0)P_1 + (a_2/a_0)P_2 + (a_3/a_0)P_3 + (a_4/a_0)P_4$ fitted by least squares to the observed angular distributions of $P^{31}(p,\gamma_0)S^{32}$. In each case the standard deviation of the coefficient is listed.

Res. energy Mev	a_1/a_0	S.D.	a_2/a_0	S.D.	a_3/a_0	S.D.	a_4/a_0	S.D.
0.825	0.07	0.05	−0.56	0.07	0.10	0.08	−0.19	0.08
1.117	0.02	0.04	−0.27	0.06	0.07	0.07	−0.05	0.06
1.248	...	...	0.4	0.1	...	...	...	...
1.892	0.04	0.03	−0.51	0.04	0.06	0.06	−0.06	0.06
1.985	−0.01	0.04	−0.01	0.05	−0.02	0.06	0.06	0.06
2.027	0.09	0.02	−0.14	0.02	−0.08	0.02	0.04	0.02
2.120	0.04	0.04	−0.58	0.06	0.16	0.06	−0.07	0.06
2.320	0.13	0.03	0.08	0.03	−0.05	0.04	0.02	0.04
2.340	0.01	0.02	−0.01	0.03	0.07	0.03	−0.09	0.03

TABLE II. The coefficients of a Legendre polynomial series $W(\theta) = P_0 + (a_1/a_0)P_1 + (a_2/a_0)P_2 + (a_3/a_0)P_3 + (a_4/a_0)P_4$ fitted by least squares to the observed distributions of $P^{31}(p,\gamma_1)S^{32*}$ for transitions to the first excited state. In each case the standard deviation is listed.

Res energy Mev	a_1/a_0	S.D.	a_2/a_0	S.D.	a_3/a_0	S.D.	a_4/a_0	S.D.
0.816	−0.02	0.02	0.37	0.03	−0.02	0.04	0.06	0.04
1.146	−0.02	0.02	0.17	0.02				
1.248	0.04	0.01	0.31	0.01	0.04	0.02	−0.03	0.01

explanation for this discrepancy may lie in the fact that Smith *et al.* used a target which was about 50 kev thick at this energy. Because of this there may have been some contribution from the resonance 80 kev lower in energy, which shows a strong transition to the first excited state of S^{32}. In the present work the target thickness in this region of energy was about 1 kev.

DISCUSSION

Theoretical expressions for the angular distribution of the proton capture gamma ray which proceeds directly to the ground state of S^{32} from the reaction $P^{31}(p,\gamma_0)S^{32}$ are particularly simple because the spin and parity for the ground state of P^{31} and S^{32} are $\frac{1}{2}+$ and 0+ respectively. For example if incoming orbital angular momenta of four units (*g*-waves) or higher are neglected the only compound states that involve a mixture of orbital momenta are those having spin and parity of 1+ and 2−, and both of these involve only channel spin 1. All of the other compound states for which ground-state gamma radiation is either dipole or quadrupole involve only a channel spin mixture. No multipole mixtures occur since the final state for the gamma transition has zero spin. That is, on these assumptions only one parameter is involved for each case.

The coefficients for such angular distributions expressed as Legendre polynomial expansions are conveniently obtained from tables prepared by Sharp *et al.*,[12] and in Table III the theoretical values of the coefficients of P_2 and P_4 are shown. The maximum and minimum values for each coefficient are also listed in Table III on the completely general assumption that the ratio of squares of matrix elements which differ in one quantum number can range from zero to infinity, and where a ratio of matrix element amplitudes occurs the phase difference is arbitrary. From these maximum and minimum values it can be seen that any measured angular distribution of the ground-state gamma transition which has a P_2 coefficient less than 5/14 involves a compound nucleus of $J=1\pm$. In addition, Table III lists the values of the coefficients predicted[12] if *jj* or *ls* coupling obtains in the compound system.

The angular distributions of the transitions to the first excited state of S^{32} at 2.25 Mev[8] are of interest because the spin of this level is not known. There is evidence[13] that it has positive parity with $J=1$, 2, or 3. The angular distributions in this case are more complicated than those for the ground-state transition since multipole mixing may occur. However, when it is possible to measure at a given resonance in the compound nucleus the angular distribution of both the

TABLE III. Theoretical values of the coefficients of P_2 and P_4 in the angular distributions of gamma-rays from a state of spin J to one of spin 0+ in the reaction $P^{31}(p,\gamma_0)S^{32}$ with their maximum and minimum values and the values predicted on *jj* and *ls* coupling. The parameter t is the ratio of the square of matrix elements of channel spin 1 to 0 while M and φ are the ratio of matrix elements and phase difference respectively for orbital angular momentum $l=2$ to $l=0$ or $l=3$ to $l=1$ as the case may be.

J	a_2/a_0	a_2/a_0 max	a_2/a_0 min	a_4/a_0	a_4/a_0 min	a_4/a_0 max	*jj* coupling values a_2/a_0	*jj* coupling values a_4/a_0	*ls* coupling values a_2/a_0	*ls* coupling values a_4/a_0	Multipole order
1+	$-\frac{1}{2}\left\{\frac{M^2+2\sqrt{2}M\cos\varphi}{1+M^2}\right\}$	1/2	−1	0	0	0	0 −1/2	0 0	0 −1/2	0 0	$M1$
1−	$\frac{1}{2}\left\{\frac{t-2}{t+1}\right\}$	1/2	−1	0	0	0	0 −1/2	0 0	−1 +1/2	0 0	$E1$
2+	$\frac{5}{14}\left\{\frac{t+2}{t+1}\right\}$	5/7	5/14	$\frac{4}{7}\left\{\frac{2t-3}{t+1}\right\}$	−12/7	8/7	1/2 4/7	0 −4/7	5/7 5/14	−12/7 8/7	$E2$
2−	$\frac{1}{7}\left\{\frac{7/2+4M^2+\sqrt{6}M\cos\varphi}{1+M^2}\right\}$	5/7	5/14	$-\frac{4}{7}\left\{\frac{M^2+2\sqrt{6}M\cos\varphi}{1+M^2}\right\}$	−12/7	8/7	1/2 4/7	0 −4/7	1/2 4/7	0 −4/7	$M2$

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[12] Sharp, Kennedy, Sears, and Hoyle, Tables of Coefficients for Angular Distribution Analysis, Chalk River Theoretical Report CRT-556, December, 1953 (unpublished).

[13] A. E. Litherland (private communication).

TABLE IV. $R(I)$ is the theoretical ratio of the coefficient of P_2 in the angular distribution of a proton capture gamma-ray in S^{32} from the capturing state J to a final state I to that for the ground-state transition $J \rightarrow I=0+$. x^2 is the ratio of the square of matrix elements of radiation $E2$ to $M1$ occurring in the $J \rightarrow I$ transition. In such cases the maximum and minimum values of $R(I)$ are listed.

J	$R(1+)$	$R(1+)$ max	$R(1+)$ min	$R(2+)$	$R(2+)$ max	$R(2+)$ min	$R(3+)$	$R(3+)$ max	$R(3+)$ min
1+	$-\left\{\frac{\frac{1}{2}x^2 \pm 3x + \frac{1}{2}}{1+x^2}\right\}$	1.0	−2.0	$\left\{\frac{\frac{1}{2}x^2 \pm (3/\sqrt{5})x + \frac{1}{10}}{1+x^2}\right\}$	1.00	−0.40	$-2/7$		
1−	$-\frac{1}{2}$			$+\frac{1}{10}$			$+1/7$		
2+	$\frac{\frac{1}{2}x^2 \pm (7/\sqrt{5})x - 7/10}{1+x^2}$	1.58	−1.77	$\left\{\frac{-(3/14)x^2 \pm [(7/5)\sqrt{(15/7)}]x + 7/10}{1+x^2}\right\}$	1.37	−0.88	$\left\{\frac{-(4/7)x^2 \pm (\frac{2}{5}\sqrt{30})x + \frac{1}{5}}{1+x^2}\right\}$	0.72	−1.45
2−	$-7/10$			$+7/10$			$-\frac{1}{5}$		

ground-state and first excited-state gamma transition, the ratio of the two P_2 coefficients so obtained can be compared with theoretical ratios of a somewhat simpler form. The simplification results only, however, under the assumptions that the matrix elements can be factored into two parts comprising the formation and decay of the compound state, and that the formation part of the matrix element is independent of the mode of decay. Table IV lists such ratios of the P_2 coefficients for transitions from a compound state J to a final state $I=1+$, $2+$, or $3+$ to the P_2 coefficients from the same compound state to a final state $I=0+$. The only parameter which enters is the intensity mixture ratio of $E2$ to $M1$ (it is assumed that where $E1$ and $M2$ mixtures can occur, $M2$ is negligible), and is designated as x^2. The phase difference is either zero or 180°. The maximum and minimum values are obtained by assuming x^2 to vary between zero and infinity (i.e., no $E2$ to all $E2$).

The angular distributions for the ground-state gamma transition shown in Table I have P_2 coefficients less than 5/14 for all the resonances with the possible exception of that at 1.248 Mev, and as indicated above this uniquely establishes the spin for these resonances as unity. Furthermore, the $P^{31}(p,\alpha_0)Si^{28}$ reaction is resonant at three of these, at 1.892, 2.027, and 2.120 Mev. Since the long-range alpha transition leads to the ground state of Si^{28} with spin and parity $0+$, the compound states in S^{32} which resonate for this reaction must have natural parity (i.e., $0+$, $1-$, $2+$, etc.), and this uniquely establishes the spin and parity of the three resonances as $1-$. It should be remarked that the nonobservation of resonances for the (p,α_0) reaction cannot be taken as certain evidence that the states do not have natural parity, and hence the parity of the remaining $J=1$ states remains in doubt. From the known J, the factor[9] $\omega=(2J+1)/[(2s+1)(2I+1)]$ can be determined, and hence $\gamma=\Gamma_p\Gamma_\gamma/\Gamma$. In Table V it has been assumed that $\Gamma \simeq \Gamma_p$, and hence Γ_γ is listed. It is interesting to note that six of the eight resonances with $J=1\pm$ have either 0 or $-\frac{1}{2}$ for the P_2 coefficient, which are the values in the limits of either jj or ls coupling. Two of the three $J=1-$ states have the value predicted in the limit of jj coupling, but not in the ls coupling limit. The third state does not agree with either the jj or ls coupling values.

The three resonances for which angular distributions of the gamma transition to the first excited state of S^{32} could be measured have their coefficients listed in Table II. Only one of these shows a measurable transition to the ground state of S^{32}, and hence is the only case in which a spin assignment can be given subject to the assumptions made in computing Table IV. At this resonance (1.248 Mev) the ratio of the P_2 coefficient for the first excited state transition to that for the ground state is 0.8 ± 0.2. Referring to Table IV, it can be seen that $J=1+$ or $2\pm$ could give the ratio. The angular distribution of the ground-state gamma transition at this resonance has $a_2/a_0=0.4\pm0.1$, and from Table III it can be seen that this is smaller than a_2/a_0 maximum for all values of J listed. However, if one makes the further assumption of time invariance,[14] the phase difference between matrix elements involving different orbitals is no longer arbitrary, but consists only of a Coulomb and hard-sphere contribution. When this is calculated for a radius of 5.8×10^{-13} cm, the upper limit of a_2/a_0 for a $J=1+$ to $I=0+$ transition is $+0.14$. On this argument, the spin and parity

TABLE V. Resonances in S^{32} for the ground-state gamma transition. Column 1 lists the proton energy of the resonance. Column 2 lists $\omega\gamma=\frac{1}{4}(2J+1)\Gamma_p\Gamma_\gamma/\Gamma$, where the spin of the level J and parity is listed in Column 3. Column 4 lists $\Gamma_{\gamma0}$, the partial width for emission of the gamma ray to the ground state obtained from Columns 2 and 3 with the assumption that the partial width for formation Γ_p is substantially equal to the total width. Column 5 lists the character of the gamma transitions to the ground state. Column 6 lists the total width where it can be measured, while Column 7 lists its ratio to the p-wave sum rule limit for the four p-wave resonances.

1. E_p (Mev)	2. $\omega\gamma$ (ev)	3. J	4. $\Gamma_{\gamma0}$ (ev)	5. Radiation	6. Γ (kev)	7. θ^2
0.825	0.09	1±	0.12	$M1$ or $E1$		
1.117	0.47	1±	0.63	$M1$ or $E1$		
1.248	0.06	2±	0.048	$E2$ or $M2$		
1.892	9.2	1−	12.0	$E1$	24	0.31
1.985	3.3	1±	4.4	$E1$ or $M1$	10	
2.027	6.5	1−	8.7	$E1$	24	0.23
2.120	1.0	1−	1.3	$E1$	5	0.04
2.320	5.0	1±	6.7	$M1$ or $E1$	8	
2.340	16.0	1±	21.0	$M1$ or $E1$	8	

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[14] We are indebted to W. T. Sharp for advice on this point.

TABLE VI. Resonances in S^{32} which have proton capture gamma-ray transition probabilities to the first excited state of $S^{32}(\gamma_1)$ much higher than those to the ground state. At each of these resonances the measured value of ω_γ for γ_1 is listed. For one of these the spin J of the compound state and hence the partial width Γ_γ for emission of γ_1 is determined.

E_p Mev	$\omega\gamma$ (ev)	J	$\Gamma\gamma$ (ev)	Radiation
0.816	0.44			
1.146	0.54			
1.248	0.92	2±	0.74	$M1$, $E2$, or $E1$

for the 1.248-Mev resonance is $J=2\pm$. If the spin and parity is $2-$, reference to Table IV shows that the spin of the first excited state in S^{32} is $2+$. If, however, $J=2+$, no choice between $1+$, $2+$, and $3+$ for the first excited state can be made until the $M1$-$E2$ mixture in the gamma transition to this state is known. An assignment of $J=2-$ is favored over $J=2+$, because the (p,α_0) reaction is not observed at this resonance, although this is not a conclusive argument.

The measured partial widths[15] for the transition to the ground state are listed in Column 4 of Table V, and for the transition to the first excited state in Column 4 of Table VI. For comparison the $E1$ transition probabilities were calculated using a four-nucleon model in *jj* coupling[16] for two possible $J=1-$ configurations for the initial state, and simple configurations for a $0+$ ground state and a $2+$ first excited state. These values are listed in Table VII. In these calculations the assumption was made that the capturing state had total isotopic spin 1 and that the ground state of S^{32} had total isotopic spin 0. Comparing these calculated ground state partial widths with the three observed $E1$ values in Table V indicates that they are at least 20 times too large. Since these three resonances are also resonant for the (p,α_0) reaction, it is probable that they have total isotopic spin zero and that the presence of $E1$ radiation reflects the small admixture of $T=1$. However, the ratio of $\Gamma_{\gamma 0}/\Gamma_{\gamma 1}$ listed in Table VII should be somewhat less sensitive to the character of the capturing state. Two of the known $J=1-$ states have coefficients of P_2 in the angular distribution of the ground-state gamma ray equal to -0.5 within the experimental uncertainty indicating the configuration $(s_{\frac{1}{2}})^3(p_{\frac{3}{2}})$ for the capturing state. These would be expected to show practically no first excited-state transition, and indeed at one of these resonances (1.887 Mev) this is so, as shown from the gamma-ray spectrum of Fig. 3. Here the ratio of $\Gamma_{\gamma 0}/\Gamma_{\gamma 1}$ is greater than 100. However, at the other resonance (2.120 Mev) the ratio is about three.

The observed total widths of the three $J=1-$ states may be assumed to be all proton widths, and are compared to the theoretical single particle width in Table V. In Column 7 the quantity θ^2 is the ratio of the reduced particle width to $(\hbar^2/Ma^2)(C^{T_p\tau T})^2$ which is expected to be close to the theoretical single particle reduced width.[17] The interaction radius a used was 5.80×10^{-13} cm. The Clebsch-Gordan coefficient involving the isotopic spins of the parent state $T_p=\frac{1}{2}$, of the emitted particle $\tau=\frac{1}{2}$, and the compound state $T=0,1$, has the value $\frac{1}{2}$ for both values of T. The reduced proton width is defined as $\gamma^2=(\Gamma_p/2ka)(F_l^2+G_l^2)$, where Γ_p is the observed width, k the proton wave number, and F_l and G_l the usual Coulomb functions. It can be seen that these three states together constitute about 60 percent of the single particle width. It may be that this effect arises from a coupling between a state of $J=1-$ of simple configuration and several states of $J=1-$ having complex configurations. Mixing effects of this kind have been described by Bohr and Mottelson[18] and Thomas.[19]

TABLE VII. Gamma-ray transition probabilities from an initial proton capture level at 10 Mev in S^{32} to ground and first excited state, assuming a simple four-particle configuration in *jj* coupling for the three nucleons in P^{31} $(s_{\frac{1}{2}})^3$ and the added proton. The last two columns list the ratio of the transition probabilities for the ground-state transition (γ_0) to that for the first excited state (γ_1) and the coefficient a_2/a_0 of P_2 in the angular distribution. These transition probabilities assume $T=1$ for the initial state and $T=0$ for the ground and first excited state in S^{32}.

Initial state	Final state Ground state $(s_{\frac{1}{2}})^4 0+$	 First excited state $(d_{\frac{3}{2}})^1(s_{\frac{1}{2}})^3 2+$	Ratio $\Gamma(\gamma_0)/\Gamma(\gamma_1)$	a_2/a_0
$(s_{\frac{1}{2}})^3p_{\frac{1}{2}}$	250 ev	77 ev	3.3	0
$(s_{\frac{1}{2}})^3p_{\frac{3}{2}}$	500 ev	1.6 ev	330	$-\frac{1}{2}$

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[15] There is an uncertainty of ±10% in the values of the partial widths due to a lack of detailed knowledge of the composition of zinc phosphide targets after evaporation.

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