^{33}P: Angular Correlation Studies of Excited States*

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The ^{31}P$(t,p)^{33}$P reaction has been used to investigate the spins and decay modes of many of the levels of ^{33}P below an excitation energy of 6.17 MeV, as well as the multipole mixing ratios of the transitions between these levels. γ radiation was detected simultaneously in five NaI(Tl) detectors located at angles equivalent to 5, 35, 45, 60, and 90°, while outgoing protons were detected in an annular detector placed at 180° with respect to the beam direction. Multiparameter techniques were used to measure the p-γ coincidence spectra. Spin assignments were confirmed for the following levels [E_x (MeV) (J)]: 1.43($\frac{3}{2}$), 1.85($\frac{5}{2}$), 2.54($\frac{3}{2}$), 3.28($\frac{3}{2}$ or $\frac{5}{2}$), 3.63($\frac{7}{2}$), 4.05($\frac{3}{2}$ or $\frac{5}{2}$), 4.22($\frac{7}{2}$). Assignments were made for these levels: 3.49($\frac{5}{2}$), 4.19($\frac{5}{2}$), 4.86($\frac{3}{2}$), 5.05($\frac{3}{2}$), 5.56($\frac{3}{2}$), 5.66($\frac{1}{2}$, $\frac{3}{2}$), 5.73($\frac{3}{2}$).

I. INTRODUCTION

Until quite recently, very little was known about the nuclear structure of ^{33}P. Within the last few years, however, the ^{30}Si$(\alpha,p)^{33}$P reaction has been used by a number of investigators[1-5] both to study the γ-ray spectroscopy[1,2,4] of some of the lower-lying levels and to obtain accurate excitation energies of states up to 6.559 MeV.[1,3-5] In addition, the ^{31}P$(t,p)^{33}$P reaction has been used to study the two-particle stripping to excited states below 5.78 MeV[6] and to obtain accurate energies for the γ rays arising from the decay of the first two excited states.[7] The ^{34}S$(d,{}^3$He$)^{33}$P reaction has also been studied.[5] A recent comprehensive paper by Harris, Nagatani, and Olness[8] describes the use of the ^{31}P$(t,p\gamma)^{33}$P reaction and NaI(Tl) and Ge(Li) γ-ray spectroscopy to investigate the spins and decay modes of excited states below 4.22 MeV. In the present work we have used a five-crystal γ-ray spectrometer in coincidence with an annular-particle detector to investigate the spins and decay modes of many of the levels below 6.18 MeV. A level scheme and partial decay scheme for excitation energies of less than 6.18 MeV is shown in Fig. 1. The diagram is a synthesis of the results of the present and previous work.

II. EXPERIMENTAL

The ^{31}P$(t,p\gamma)^{33}$P reaction ($Q=+9.558$ MeV) was used to populate excited states in the residual nucleus. The bombarding energy was 2.9 MeV and a beam current of approximately 40 nA was used. An attempt was made to produce an elemental red phosphorus target by evaporation,[9] and targets of approximately 200 μg/cm^2 thickness were obtained. These, however, were heavily contaminated with oxygen and to a lesser extent with nitrogen. The

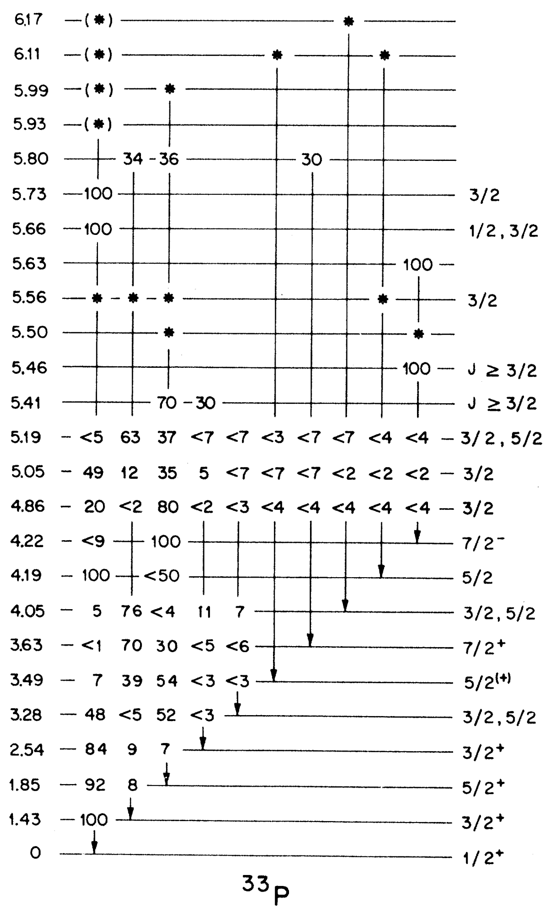

FIG. 1. Level scheme and partial decay scheme for levels of excitation energy less than 6.18 MeV in ^{33}P. The spin assignments and decay modes (for the levels below 4.19 MeV) are a synthesis of the present and previous work. The notation * on the figure means that the corresponding decay was seen and is probably one of the major decay modes of the level in question. The notation (*) means that the decay indicated is possible. See Ref. 15.

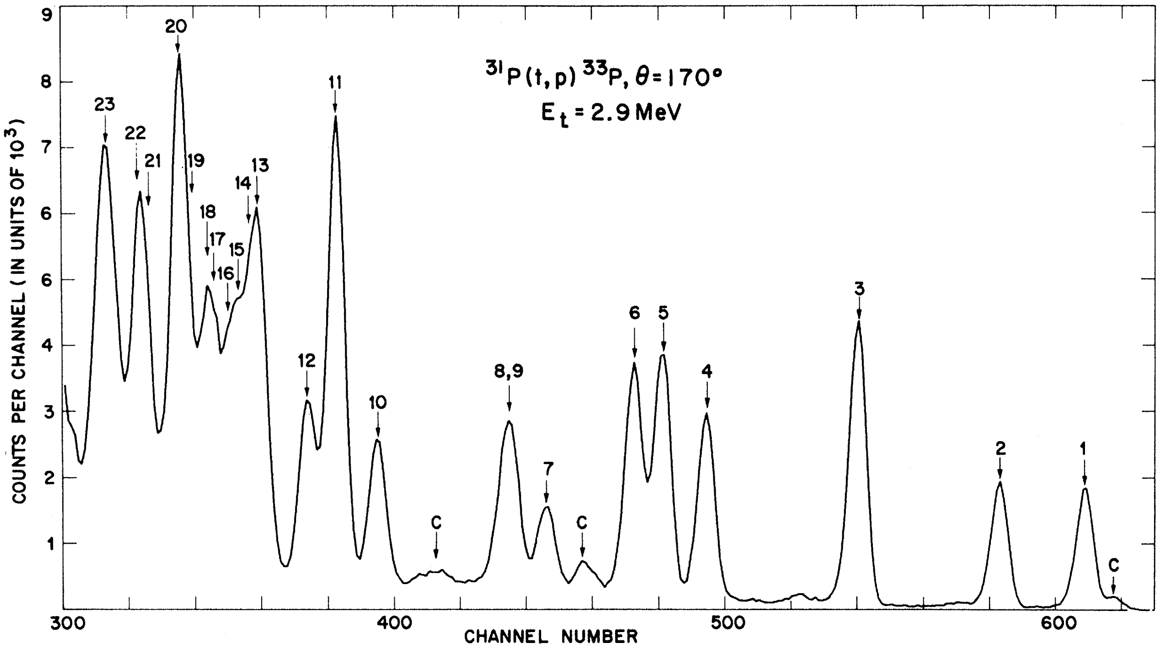

FIG. 2. The charged particle spectrum in coincidence with all γ rays of energy greater than 250 keV obtained from the annular detector ($\theta_p = 170 \pm 5°$) at a bombarding energy of 2.9 MeV. The positions of proton groups corresponding to the excitation of levels in ^{33}P are indicated by the numbered vertical arrows. These correspond to the numbering of the levels in Table I. Contaminant peaks are indicated by *c*.

TABLE I. Decay modes in ^{33}P determined in present work. The asterisk indicates that a γ ray corresponding to the indicated transition was observed. It was not possible, however, to determine the percentage branching.

	Decay to state	0	1.43	1.85	2.54	3.28	3.49	3.63	4.05	4.19	4.22
1	1.43	100									
2	1.85	92 ± 2	8 ± 2								
3	2.54	85 ± 3	8 ± 1	7 ± 1							
4	3.28	48 ± 3	<5	52 ± 3	<3						
5	3.49	7 ± 2	44 ± 3	49 ± 3	<3	<3					
6	3.63	<1	67 ± 4	33 ± 4	<5	<6	<4				
7	4.05	<5	83 ± 9	<9	<13	17 ± 9	<4	<4			
8	4.19 [a]	100		<50							
9	4.22 [a]	<9		100							
10	4.86	20 ± 4	<2	80 ± 4	<2	<3	<4	<4	<4	<4	<4
11	5.05	49 ± 4	12 ± 4	35 ± 5	5 ± 2	<7	<7	<7	<2	<2	<2
12	5.19	<5	63 ± 4	37 ± 4	<7	<7	<3	<7	<7	<4	<4
13	5.41			70 ± 10	30 ± 10						
14	5.46										100
15	5.50			*							*
16	5.56	*	*	*						*	
17	5.63 [b]										100
18	5.66	100									
19	5.73	100									
20	5.80		34 ± 10	36 ± 10				30 ± 10			
21	5.93	(*) [c]									
22	5.99	(*)		*							
23	6.11 [b]	(*)					*			*	
24	6.17	(*)							*		

[a] Reference 8. [b] New level. [c] Indicates a possible transition.

TABLE II. Adopted decay modes in ^{33}P: levels below 4.1 MeV.

	0	1.43	1.85	2.54	3.28
1.85	92 ± 2	8 ± 2			
2.54	84 ± 2	9 ± 1	7 ± 1		
3.28	48 ± 3	<5	52 ± 3	<3	
3.49	7 ± 2	39 ± 4	54 ± 4	<3	<3
3.63	<1	70 ± 3	30 ± 3	<5	<6
4.05	5 ± 3	76 ± 4	<4	11 ± 4	7 ± 3

^{16}O$(t, p\gamma)^{18}$O reaction ($Q = +3.705$ MeV) has a cross section which is considerably higher than the corresponding tritium-induced reaction on phosphorus, consequently the most intense lines in the particle spectrum corresponded to excitation of the ground and first excited states of ^{18}O. Fortunately, however, the Q values are sufficiently different that the particle groups corresponding to the levels of interest in ^{33}P were considerably more energetic than the contaminant groups, except for the states of highest excitation energy investigated. For these states, some contamination from the ^{14}N$(t, p\gamma)^{16}$N reaction was observed. The protons were detected in an annular detector at 180° while the coincident γ rays were detected in five 10.16-cm × 10.16-cm NaI(Tl) detectors at angles equivalent to 5, 35, 45, 60, and 90° with respect to the beam as axis. The particle spectrum in coincidence with all γ rays is shown in Fig. 2. The arrangement of the electronics to handle the simultaneous outputs from the five NaI(Tl) detectors and to determine events coincident with the detection of protons in the annular detector was similar to that described by Chalmers.[10] Each event was stored on magnetic tape using a general purpose SEL-810A computer. In addition to the detectors described above a small piece of NE102 (1.8 cm × 1.8 cm × 0.3 cm) mounted on a photomultiplier could detect β particles from a ^{228}Th source placed near the detector (and near the target). These pulses could then be used to flag real β-γ coincident events. The γ spectrum associated with these events was also stored on magnetic tape. This enabled the gains and efficiencies of all five detectors to be monitored during the experiment and in the later off-line analysis of the data. The gains of all five detectors were adjusted to be as nearly equal as possible before the run. Following this, however, they drifted somewhat, consequently in later off-line analysis the gains were stabilized using the strong 1.98-MeV line corresponding to deexcitation of the first excited state of ^{18}O. In addition, their gains were forced to be the same,

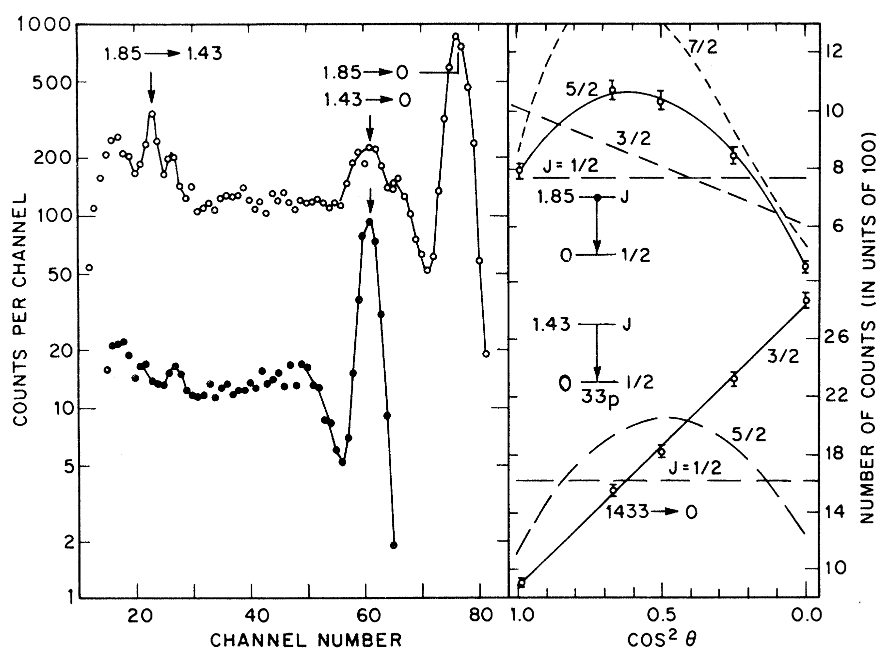

FIG. 3. The spectra on the left of the figure represent the γ-ray decay of the levels at 1.43 and 1.85 MeV in ^{33}P as observed in a 10.16-cm-diam × 10.16-cm NaI(Tl) detector. Note the photopeak at channel 23 in the uppermost spectrum which corresponds to an energy of 417 keV and is characteristic of the decay of the 1.85-MeV level. The angular correlations and the best-fitting curves for varying spin assignments to these levels are shown in the right-hand side of the figure.

TABLE III. Summary of p-γ correlation measurements. The Legendre polynomial coefficients a_2 and a_4 extracted from the observed angular correlations have not been corrected for the finite solid angles subtended by the NaI(Tl) detectors at the target. In the subsequent analysis the attenuation coefficients Q_2 and Q_4 were taken as 0.95 and 0.86, respectively.

E_i (MeV)	Transition $E_i \rightarrow E_f$	a_2	a_4	χ^2	E_i (MeV)	Transition $E_i \rightarrow E_f$	a_2	a_4	χ^2
1.43	1.43 → 0	−0.60 ± 0.02	0.01 ± 0.02	0.31		1.85 → 0	+0.45 ± 0.06	−0.26 ± 0.06	0.47
1.85	1.85 → 0	+0.48 ± 0.03	−0.49 ± 0.04	0.34	4.86	4.86 → 0	+0.06 ± 0.07	+0.02 ± 0.07	1.08
	1.85 → 1.43	−0.22 ± 0.12	+0.06 ± 0.11	1.39		4.86 → 1.85	+0.06 ± 0.04	+0.01 ± 0.04	0.60
	1.43 → 0	−0.16 ± 0.10	···	1.33		1.85 → 0	−0.18 ± 0.07	+0.01 ± 0.07	0.23
2.54	2.54 → 0	−0.09 ± 0.02	−0.02 ± 0.02	3.87	5.05	5.05 → 0	−0.50 ± 0.03	+0.01 ± 0.03	0.86
3.28	3.28 → 0	−0.03 ± 0.04	+0.10 ± 0.04	2.78		5.05 → 1.85	−0.02 ± 0.10	+0.10 ± 0.10	1.35
	3.28 → 1.85	+0.01 ± 0.04	+0.02 ± 0.04	0.66		1.85 → 0	+0.28 ± 0.05	+0.01 ± 0.05	0.71
	1.85 → 0	+0.00 ± 0.05	+0.00 ± 0.05	0.63	5.19	5.19 → 1.43	−0.35 ± 0.09	+0.21 ± 0.09	2.60
3.49	3.49 → 0	+0.06 ± 0.09	+0.09 ± 0.09	0.01		1.43 → 0	−0.58 ± 0.07	−0.03 ± 0.07	0.19
	3.49 → 1.43	−0.48 ± 0.07	+0.01 ± 0.06	0.74		5.19 → 1.85	+0.25 ± 0.14	+0.10 ± 0.13	0.59
	1.43 → 0	−0.36 ± 0.06	+0.03 ± 0.06	0.58		1.85 → 0	+0.19 ± 0.12	−0.02 ± 0.12	2.54
	3.49 → 1.85	+0.31 ± 0.06	+0.00 ± 0.06	1.12	5.41	5.41 → 1.85	+0.02 ± 0.07	+0.05 ± 0.07	1.30
	1.85 → 0	+0.29 ± 0.05	−0.10 ± 0.05	0.83		1.85 → 0	+0.25 ± 0.06	−0.03 ± 0.06	0.45
3.63	3.63 → 1.43	+0.47 ± 0.05	−0.18 ± 0.05	4.70	5.46	5.46 → 4.22	+0.58 ± 0.11	0.18 ± 0.11	0.41
	1.43 → 0	−0.60 ± 0.06	+0.00 ± 0.05	0.35		4.22 → 1.85	−0.40 ± 0.11	+0.16 ± 0.11	0.29
	(3.63 → 1.85 + 1.85 → 0)	−0.31 ± 0.07	+0.12 ± 0.07	0.71		1.85 → 0	+0.27 ± 0.07	−0.07 ± 0.07	1.85
4.05	4.05 → 1.43	−0.01 ± 0.12	+0.13 ± 0.13	1.24	5.56	5.56 → 0	−0.35 ± 0.06	−0.03 ± 0.06	0.66
	1.43 → 0	−0.48 ± 0.07	+0.08 ± 0.06	2.90	5.66	5.66 → 0	+0.04 ± 0.04	−0.05 ± 0.04	0.25
4.19	4.19 → 0	−0.01 ± 0.08	+0.04 ± 0.08	0.08	5.73	5.73 → 0	−0.31 ± 0.03	+0.01 ± 0.03	2.13
4.22	4.22 → 1.85	−0.33 ± 0.06	+0.06 ± 0.06	1.88	5.99	1.85 → 0	+0.36 ± 0.10	+0.03 ± 0.11	0.25

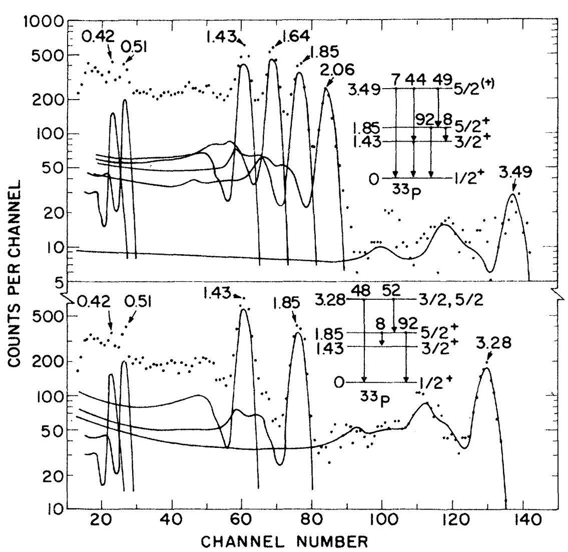

FIG. 4. The summed γ-ray spectra in coincidence with protons feeding the 3.28- and 3.49-MeV levels. The contributions of individual γ rays are indicated by the continuous lines. The 7% ground-state decay of the 3.49-MeV level is clearly seen. The peak at channel 23 corresponds to the 417-keV decay of the 1.85-MeV level to the 1.43-MeV level. Peaks are labeled by the γ-ray energy in MeV.

thus facilitating subsequent analysis. (In the same way the gain of the particle detector was also stabilized *ex post facto*.) In complex spectra the angular distributions of interest were extracted using the known γ-ray line shapes for 10.16-cm × 10.16-cm NaI(Tl) crystals. Extraction of the angular correlations and peak areas of all reasonably strong γ rays was straightforward for all levels with excitation energies less than 5.4 MeV except for the doublet reported by Harris, Nagatani, and Olness[8] at 4.2 MeV. For excitation energies greater than 5.4 MeV the resolution of the particle detector was insufficient to resolve the individual levels and only major decay modes and (generally) angular correlations of ground-state transitions could be obtained.

III. RESULTS

Table I presents a summary of the decay modes of the excited states in ^{33}P below 6.17 MeV as determined in the present work. For the levels below 5.4 MeV, the results are obviously more complete than for higher excited states, reflecting the fact that the particle groups corresponding to population of the former levels were in general resolved in the annular detector. For the latter group of states we could, in general, determine only whether or not a given decay mode appeared with some reasonable intensity. For the levels below 4.1 MeV, we have combined our results with those of previous investigators and present the adopted decay modes in Table II.

A summary of the particle-γ correlation measurements is given in Table III. Each correlation was fitted by the method of least squares to an expression of the form $A_0[1+a_2P_2(\cos\theta)+a_4P_4(\cos\theta)]$: The values of a_2, a_4, and the normalized χ^2 are shown in the table. Since the ground-state spin of ^{31}P is $\frac{1}{2}$, and because of the particular detection geometry used, only the magnetic substates $m = \pm\frac{1}{2}$, $\pm\frac{3}{2}$ are selected in the residual states of ^{33}P. The angular distributions were consequently further analyzed following the method of Poletti and Warburton.[11] The individual results will now be discussed.

1.43- and 1.85-MeV Levels

The spins of these levels were verified to be $\frac{3}{2}$ and $\frac{5}{2}$, respectively. The summed γ-ray spectra in coincidence with protons feeding these levels are displayed in Fig. 3 along with the measured angular correlations and best-fitting curves for varying spin assignments. In the figure, the spectrum for the 1.43-MeV level has been scaled by a factor of 0.083 in order to display the contribution to the spectrum in coincidence with protons feeding the 1.85-MeV level due to the 8% decay to the 1.43-MeV level. From a simultaneous least-squares fit of the angular distributions of the 1.85- to 1.43-MeV and the 1.85–0-MeV γ rays, the mixing ratio of the 1.85- to 1.43-MeV transition was found to be $x = -0.09 \pm 0.18$. A second solution was rejected since the resultant mixing ratio implied that the possible $E2$ transition had a strength greater than 370 Weisskopf units (W.u.).[12]

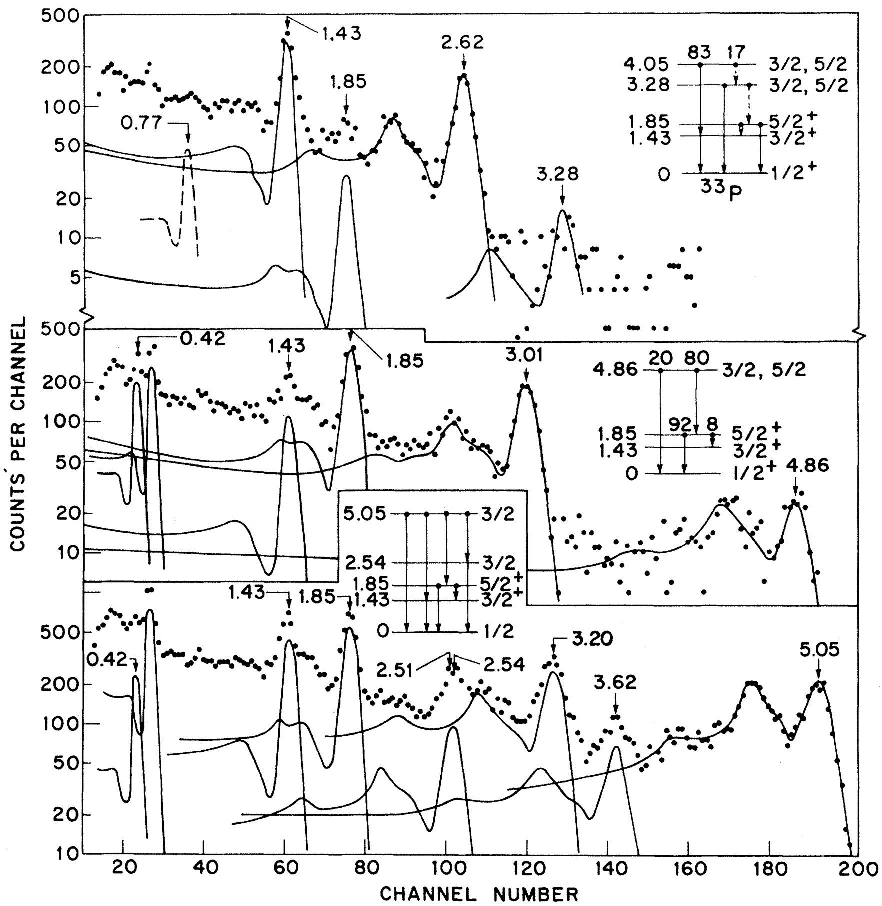

FIG. 5. The summed γ-ray spectra in coincidence with protons feeding the 4.05-, 4.86-, and 5.05-MeV levels. The line shapes of the constituent γ rays are indicated.

2.54- and 3.28-MeV Levels

The decay modes established by Harris, Nagatani, and Olness[8] for the 2.54-MeV level were verified. The summed spectrum in coincidence with protons feeding the 3.28-MeV level is shown in the lower part of Fig. 4. Harris, Nagatani, and Olness[8] were unable to determine whether the cascade decay was through the 1.85- or the 1.43-MeV level. However, a signature for decay to the 1.85-MeV level is the appearance of a peak at 417 keV due to the 8% decay of this level to the 1.43-MeV level. A comparison of the spectra shown in Figs. 3 and 4 showed that no more than 5% of the decays of the 3.28-MeV level can be through the 1.43-MeV level. We determined the decay to be $(48\pm3)\%$ to the ground state and $(52\pm3)\%$ to the 1.85-MeV level. The angular distributions observed in coincidence with the proton groups feeding both levels were all close to isotropic. However, the spin assignment of $\frac{3}{2}$ to the 2.54-MeV level was verified while in the case of the 3.28-MeV level both $J=\frac{3}{2}$ and $\frac{5}{2}$ were allowed. Our decay mode measurements agree with those of Wagner *et al.*[13]

3.49-MeV Level

The summed γ-ray spectrum in coincidence with protons feeding this level is shown in the upper part of Fig. 4. Our determination of the decay modes is in reasonable agreement with the work of Harris, Nagatani, and Olness,[8] but is considerably more accurate. In particular, we have been able to establish the existence of a $(7\pm2)\%$ decay to the ground state: $J\leq\frac{5}{2}$ is implied by the angular distribution of this γ ray. The angular distributions of the four cascade γ rays were all quite anisotropic, hence only $J=\frac{3}{2}$ or $\frac{5}{2}$ are al-

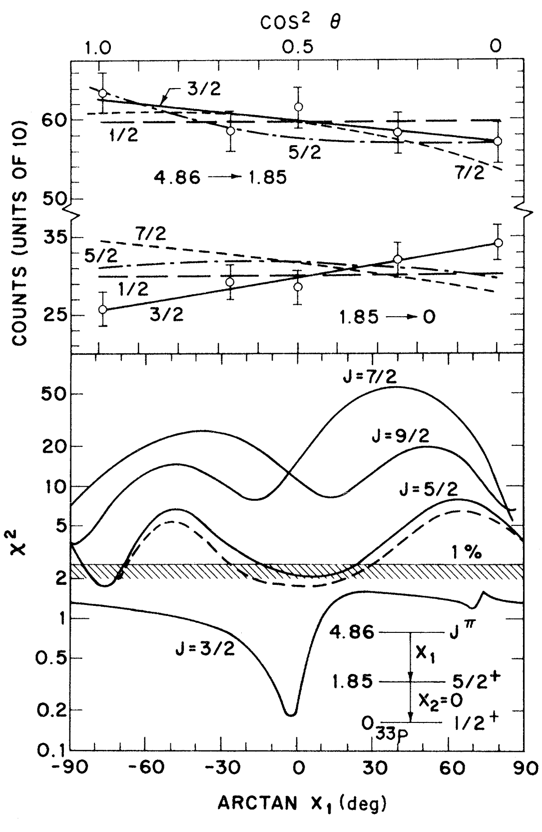

FIG. 6. The angular correlations for the cascade transitions from the 4.86- to the 1.85-MeV level are displayed in the upper part of the figure together with the best fitting curves for spin assignments from $J=\frac{1}{2}$ to $J=\frac{7}{2}$. In the lower part of the figure is shown a plot of χ^2 versus arctan x_1, where x_1 is the mixing ratio of the 4.86- to 1.85-MeV transition. The dashed line gives an estimate of the effect of the finite size of the annular detector on the value of χ^2 calculated for $J=\frac{5}{2}$.

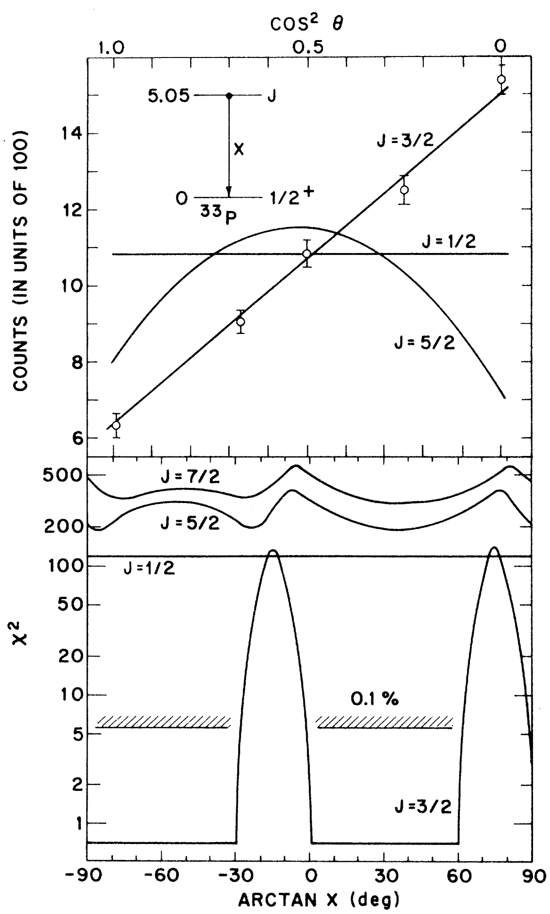

FIG. 7. The observed angular correlations and calculated best-fitting distributions for the ground-state transition from the 5.05-MeV level. $J=\frac{3}{2}$ is clearly preferred.

lowed. A simultaneous fitting of the 3.49- to 1.43-MeV and 1.43- to 0-MeV angular distributions gave fits for both spin possibilities, however, for $J=\frac{3}{2}$, the mixing ratio which was determined for the 3.49- to 1.43-MeV transition ($x=-2.6\pm 1.4$) does not overlap with a previously determined[4] mixing ratio ($x=+1.35\pm 0.20$). Hence $J=\frac{3}{2}$ is eliminated as a possible spin assignment for the 3.49-MeV level. For $J=\frac{5}{2}$, $x=+(0.37\pm 0.28)$ for the transition to the 1.43-MeV level, while for the transition to the 1.85-MeV level, $-2.1<x<+0.27$. The mixing ratio for the decay to the ground state is $x=-0.07\pm 0.07$. If the parity of the 3.49-MeV level is odd, the transition to the ground state would have an $M2$ strength of at least 1.4 W.u.,[12] which is unlikely. This level therefore most probably has even parity: $J^{\pi}=\frac{5}{2}^{(+)}$.

3.63- and 4.05-MeV Levels

The decay modes which we have determined for these levels are in substantial agreement with

TABLE IV. Mixing ratios and spin assignments from the present work.

Transition (MeV)	Spins J_i, J_f	Mixing ratio
1.43–0	$\frac{3}{2}$, $\frac{1}{2}$	$-20.4<x<-0.64$, $+0.05<x<1.56$
1.85–0	$\frac{5}{2}$, $\frac{1}{2}$	$+(0.048\pm 0.040)$
1.85–1.43	$\frac{5}{2}$, $\frac{3}{2}$	$-(0.09\pm 0.18)$
2.54–0	$\frac{3}{2}$, $\frac{1}{2}$	No restriction
3.28–0	$\frac{3}{2}$, $\frac{1}{2}$	No restriction
	$\frac{5}{2}$, $\frac{1}{2}$	$x>-0.36$
3.28–1.85	$\frac{3}{2}$, $\frac{5}{2}$	No restriction
	$\frac{5}{2}$, $\frac{5}{2}$	$x<-2.1$, $-0.4<x<1.0$, $x>5.7$
3.49–1.43	$\frac{5}{2}$, $\frac{3}{2}$	$+(0.37\pm 0.28)$
3.49–1.85	$\frac{5}{2}$, $\frac{5}{2}$	$-2.1<x<+0.27$
3.49–0	$\frac{5}{2}$, $\frac{1}{2}$	$-(0.07\pm 0.07)$
3.63–1.43	$\frac{7}{2}$, $\frac{3}{2}$	$-(0.03\pm 0.13)$
3.63–1.85	$\frac{7}{2}$, $\frac{5}{2}$	$-(0.01\pm 0.08)$
4.05–1.43	$\frac{3}{2}$, $\frac{3}{2}$	$x<-1.88$, $0<x<0.36$, $x>1.28$
	$\frac{5}{2}$, $\frac{3}{2}$	$-0.78<x<+0.33$
4.22–1.85	$\frac{7}{2}$, $\frac{5}{2}$	$-(0.01\pm 0.08)$
4.86–0	$\frac{3}{2}$, $\frac{1}{2}$	No restriction
	$\frac{5}{2}$, $\frac{1}{2}$	$-0.35<x<-0.22$, $+0.22<x<1.57$, $x>8.1$
4.86–1.85	$\frac{3}{2}$, $\frac{5}{2}$	No restriction
	$\frac{5}{2}$, $\frac{5}{2}$	$-11.4<x<-2.5$, $-0.40<x<0.40$
5.05–0	$\frac{3}{2}$, $\frac{1}{2}$	$-0.02<x<1.8$
5.05–1.85	$\frac{3}{2}$, $\frac{5}{2}$	$+(0.22\pm 0.65)$
5.19–1.43	$\frac{3}{2}$, $\frac{3}{2}$	$x<-2.36$, $x>6.31$
	$\frac{5}{2}$, $\frac{3}{2}$	0 ± 0.33
5.19–1.85	$\frac{3}{2}$, $\frac{5}{2}$	No restriction
	$\frac{5}{2}$, $\frac{5}{2}$	No restriction
5.41–1.85	$\frac{3}{2}$, $\frac{5}{2}$	No restriction
	$\frac{5}{2}$, $\frac{5}{2}$	$x<-1.9$, $-0.29<x<1.0$
	$\frac{7}{2}$, $\frac{5}{2}$	$x<-4.7$, $-0.51<x<-0.01$, $x>4.7$
	$\frac{9}{2}$, $\frac{5}{2}$	$0<x<0.63$, $x>3.5$

those reported by Harris, Nagatani, and Olness.[8] However, in the case of the 4.05-MeV level, the summed spectrum (Fig. 5) shows evidence for a $(17\pm 9)\%$ decay to the 3.28-MeV level. We verified the spin assignment[8] of $J=\frac{7}{2}$ to the 3.63-MeV level, but were unable to differentiate between the two possibilities already suggested[8] for the 4.05-MeV level: $J=\frac{3}{2}$ or $\frac{5}{2}$. For the 3.63-MeV level the mixing ratio for the transition to the 1.43-MeV level was determined as $x=-(0.03\pm 0.13)$, while for the transition to the 1.85-MeV level, the mixing ratio was determined as $x=-(0.01\pm 0.08)$. Our decay-mode measurements are in substantial agreement with those of Wagner *et al.*[13]

4.19- and 4.22-MeV Levels

Our data were consistent with the conclusion of Harris, Nagatani, and Olness[8] that there is a doublet at about 4.2-MeV excitation energy. Our analysis assumed that the decays of these levels were primarily to the ground state in the case of the 4.19-MeV level and to the 1.85-MeV level in the case of the 4.22-MeV level. The ground-state transition was quite isotropic, hence the spin of the 4.19-MeV level could be limited only to $J\leq\frac{5}{2}$. The possibility $J=\frac{7}{2}$ was eliminated at the 0.1% confidence limit. Combining this result with that of Harris, Nagatani, and Olness[8] leads to the firm assignment of $J=\frac{5}{2}$ for this level. The results we obtained from a simultaneous analysis of the angular distributions of the cascade transition through the 1.85-MeV level were in agreement with the conclusion of Harris, Nagatani, and Olness[8]: The spin of the 4.22-MeV level is $J=\frac{7}{2}$, while the mixing ratio for the transition to the 1.85-MeV level was determined as $x=-(0.01\pm 0.08)$.

4.86-MeV Level

The summed spectrum of γ rays in coincidence with protons feeding this level is shown in Fig. 5. The level was found to decay $(80\pm 4)\%$ to the 1.85-MeV level and $(20\pm 4)\%$ to the ground state. The angular distribution of the ground-state transition allowed $J\leq\frac{5}{2}$; however, a simultaneous fit of the 4.86- to 1.85-MeV and 1.85-MeV to ground-state

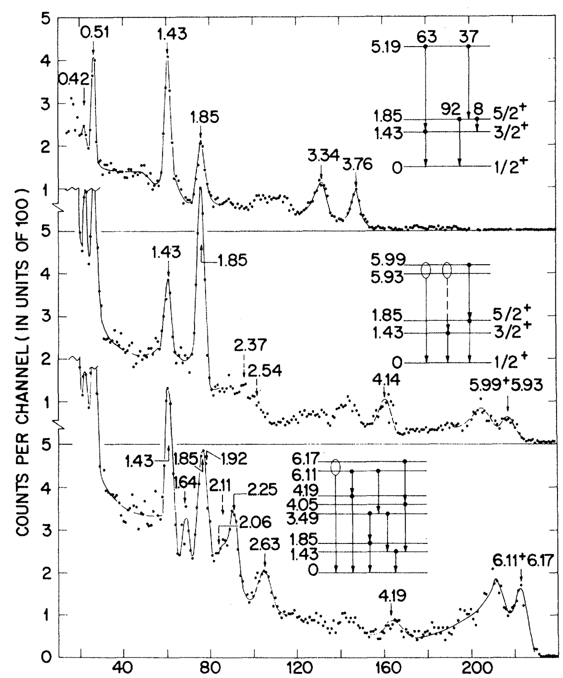

FIG. 8. γ-ray spectra in coincidence with particles corresponding to excitation of levels at 5.19-, 5.93-, 5.99-, 6.11-, and 6.17-MeV excitation energy. The large number of counts in the low channels of the lower two spectra are due to excitation of the lowest-lying states of ^{16}N by the $^{14}N(t,p)^{16}N$ reaction.

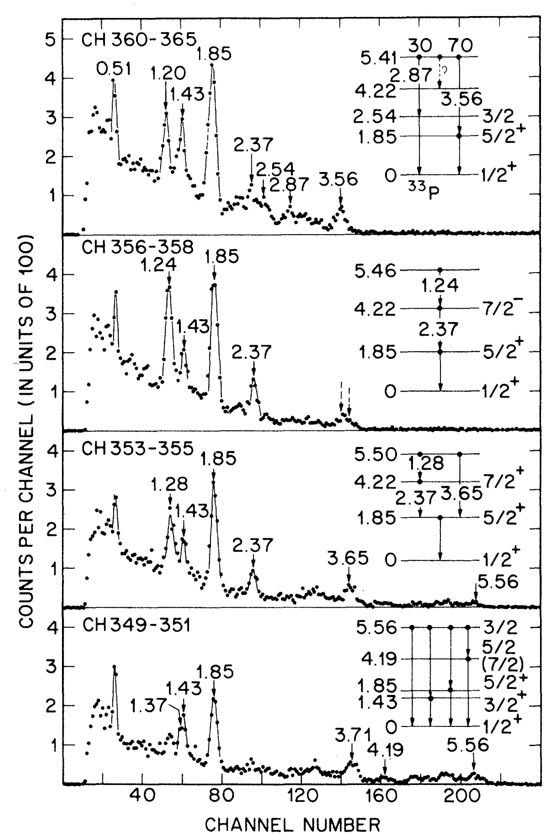

FIG. 9. γ-ray spectra in coincidence with particles corresponding to excitation of levels at 5.41-, 5.46-, 5.50-, and 5.56-MeV excitation energy. The channel numbers in the top left-hand corner of each section of the figure correspond to the gating region in the particle spectrum (see Fig. 2). The broken arrows in the second spectrum indicate the positions of contaminant lines from nearby levels.

transitions allowed $J=\frac{3}{2}$ and $\frac{5}{2}$ while $J=\frac{1}{2}$ was eliminated at the 5% confidence limit by the anisotropy of the 1.85-MeV to ground-state transition. The observed angular correlations of the two cascade γ rays and the best fitting curves for the various spin possibilities are given in Fig. 6. A plot of χ^2 versus $\tan^{-1}x$ where x is the mixing ratio of the 4.86- to 1.85-MeV transition is shown in the lower part of the same figure. Of the two possible spin assignments to this level, $J=\frac{3}{2}$ is the most favored: The lowest value of χ^2 for $J=\frac{5}{2}$, taking into account the finite size of the annular detector, lies at approximately the 7% confidence level.

5.05-MeV Level

The lowest section of Fig. 5 displays the spectrum of γ rays in coincidence with protons feeding this level. Major decay modes to the ground state (49%) and to the level at 1.85-MeV (35%) were observed. Weaker decays were also observed to the 1.43-MeV (12%) and 2.54-MeV (5%) levels. The angular distribution of the γ-ray decay to the ground state characterized the level as $J=\frac{3}{2}$. The observed distribution, together with the best-fitting curves for $J=\frac{1}{2}$ to $\frac{5}{2}$ is displayed in the upper half of Fig. 7 while χ^2 as a function of the mixing ratio for the ground-state transition is shown in the lower part of the figure. A simultaneous fit to the angular distribution of the 5.05- to 1.85-MeV and 1.85- to 0-MeV transition showed that the mixing ratio of the 5.05- to 1.85-MeV transition was +(0.22±0.65). Furthermore the limitation on the relative populations of the magnetic substates enabled us to limit the mixing ratio of the ground-state transition to $-0.02 < x < 1.80$.

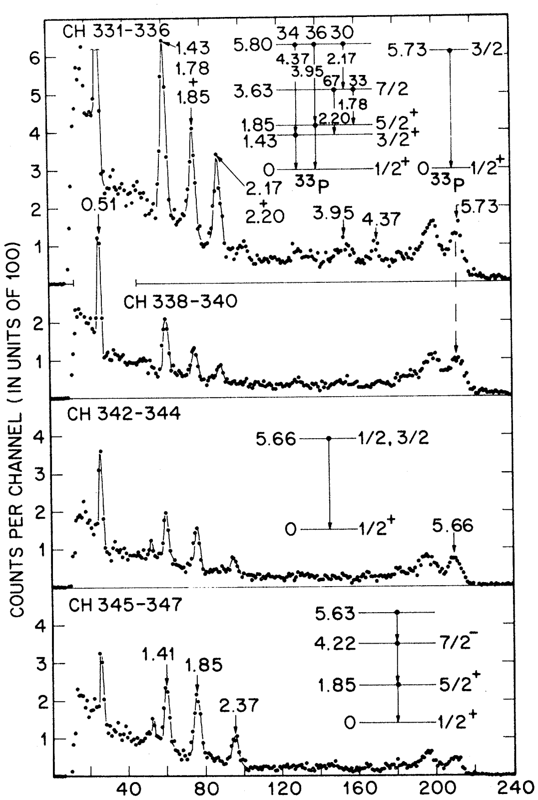

FIG. 10. γ-ray spectra in coincidence with particles corresponding to excitation of levels at 5.63-, 5.66-, 5.73-, and 5.80-MeV excitation energy. See caption of Fig. 9.

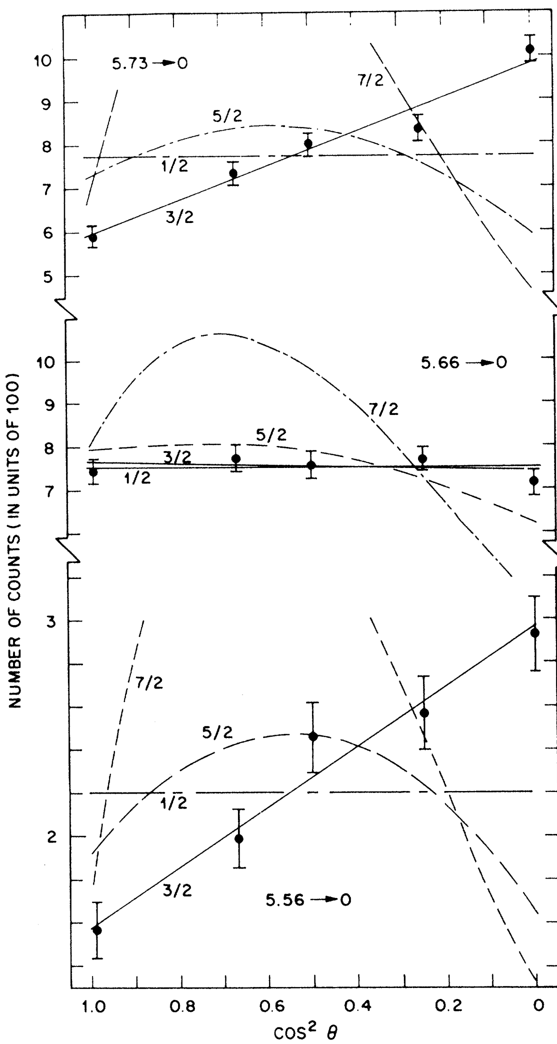

FIG. 11. Experimental angular distributions of ground-state transitions from the levels at 5.56-, 5.66-, and 5.73-MeV excitation energy. For each experimental distribution the best-fitting curves for possible spin assignments of $J=\frac{1}{2}$, $\frac{3}{2}$, $\frac{5}{2}$, and $\frac{7}{2}$ are shown.

5.19-MeV Level

The γ-ray spectrum corresponding to the decay of this level is shown in the upper part of Fig. 8. The main decay was found to be to the 1.43-MeV level $(63\pm4)\%$ with a less intense decay to the 1.85-MeV level $(37\pm4)\%$. A simultaneous analysis of the angular distributions of the 5.19- to 1.43- and 1.43- to 0-MeV transitions allowed spins of $\frac{3}{2}$ and $\frac{5}{2}$ only, while $J=\frac{7}{2}$ was rejected at the 1% confidence level. Further analysis of the distributions of the cascade γ rays through the 1.85-MeV level could not further restrict the possible spin assignments. Some restrictions on mixing ratios were obtained. These are listed in Table IV.

Levels from 5.41 to 6.18 MeV

Except for the doublet at 4.2 MeV, the resolution of the particle detector was sufficient to resolve all particle groups leading to the levels below 5.2 MeV. For the higher excited states this was not so, consequently the information which we have been able to extract from the two-parameter data is much more rudimentary for the levels with excitation energies between 5.41 and 6.18 MeV. The γ-ray spectra in coincidence with certain regions of the particle spectrum are shown in Figs. 8 to 10. We have attempted to assign decay modes from this and other data and list the best estimates which we were able to obtain in Table I. The decay of the 5.41-MeV level was mainly (70%) to the 1.85-MeV level with a weaker branch to the 2.54-MeV level (30%). The anisotropy of both the 1.43- and 1.85-MeV γ rays rules out $J=\frac{1}{2}$. The 5.46-MeV level appears to decay by a triple cascade through the 4.22- and 1.85-MeV levels. The anisotropic distribution of all three γ rays rules out $J=\frac{1}{2}$. The major decay modes of the 5.50-MeV level are to the 4.22- and 1.85-MeV levels. Decays from the 5.56-MeV level to levels at 0, 1.43, 1.85, and 4.19 MeV were seen. The angular distribution of the 5.56-MeV γ ray (Fig. 11) allowed a spin assignment of $J=\frac{3}{2}$ to be made to this level.

A careful examination of the γ-ray spectrum in coincidence with pulses from the particle detector falling in channels 342–347 (see Fig. 10) revealed that the intensity of the ground-state transition relative to the cascade transition through the 4.22-MeV level changed from one side of the peak (labeled 17 and 18 in Fig. 2) to the other. We consequently assume the existence of two levels in this region of excitation and (somewhat roughly) assign their energies as 5.63 and 5.66 MeV. The major decay of the upper level is to the ground state. The angular distribution of the corresponding γ ray (shown in Fig. 11) was quite isotropic: $J=\frac{1}{2}$ and $\frac{3}{2}$ are allowed. The lower-lying level appears to decay by a triple cascade through the 4.22-MeV level.

Analysis of the γ-ray spectra in coincidence with pulses from the particle detector falling in channels 331–340 (see Fig. 10) revealed that the major decay of the 5.73-MeV level was to the ground state. The angular distribution of the corresponding γ ray (see Fig. 11) allowed a spin assignment of $J=\frac{3}{2}$ to be made to the 5.73-MeV level. The γ-ray spectrum associated with the decay of the 5.80-MeV level was complex, but could be reasonably well understood in terms of decays to the 1.43-MeV level (34%), 1.85-MeV level (36%), and 3.63-MeV level (30%). A spin of $\frac{3}{2}$, $\frac{5}{2}$, or $\frac{7}{2}$ seems likely.

The γ-ray spectra (see Fig. 8) associated with the peaks labeled 21, 22, and 23 in the particle spectrum (see Fig. 2) were rather difficult to interpret. It appears that the 5.93-MeV level possibly decays to the ground state and first excited state while the 5.99-MeV level possibly has the same two decay modes and appears to have a firm decay to the 1.85-MeV level. The peak labeled 23 in Fig. 2 appears to be composite, corresponding to excitation of levels at 6.11 and 6.17 MeV. The 6.11-MeV level has major decay modes to the levels at 4.19 and 3.49 MeV and possibly to the ground state, while the 6.17-MeV level appears to decay mainly to the level at 4.05 MeV with a possible branch to ground.

IV. DISCUSSION

The decay modes which we have measured for the levels below 4.1 MeV are generally in good agreement with those determined by Harris, Nagatani, and Olness.[8] Two points should be noted: We observed a definite ground-state branch from the 3.49-MeV level and although we agree with Harris, Nagatani, and Olness[8] that the main decay mode of the 4.05-MeV level is to the 1.43-MeV state, our data seem to be best explained by including the possibility of a weaker decay to the 3.28-MeV level. For the levels below 4.19 MeV, the decay mode measurements of Wagner *et al.*[13] are in substantial agreement with our own. These were included in the averaging procedure used in obtaining the results presented in Table II.

It is still rather difficult to form any coherent picture of the nuclear structure of ^{33}P; the present work has, however, filled out some of the details. The measured value of $x=-(0.09\pm0.18)$ for the 1.85- to 1.43-MeV mixing ratio, together with the lifetime[2] of $\tau=1.36\pm0.17$ psec and the established $(8\pm2)\%$ branch to the 1.43-MeV level enables us to compare the predictions of Wildenthal *et al.*[14] with the measured $M1$ strength of the transition. We obtain an $M1$ strength of (0.025 ± 0.008) W.u. while the prediction of Ref. 14 using the free-parameter surface delta interaction model is that the $M1$ strength is 0.029 W.u., in good agreement. Although a second $\frac{1}{2}^+$ level is predicted[14] at $E_x = 3.64$ MeV, there are no experimental candidates for this state below 5.46 MeV, while the lowest-lying candidate for the $\frac{9}{2}^+$ level predicted at 4.14 MeV is the 5.46-MeV state which appears to decay entirely to the $\frac{7}{2}^-$ level at 4.22 MeV.

Obviously a great deal more definitive information could be obtained concerning the level structure of ^{33}P if the radiative widths of the levels above 2.0 MeV could be measured. We have finished a program aimed at a determination of those widths and will include a more detailed discussion with the description of that work.[15]

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[1]C. E. Moss, R. V. Poore, N. R. Roberson, and D. R. Tilley, Phys. Rev. 174, 1333 (1968).

[2]W. M. Currie, L. G. Earwaker, J. Martin, and A. K. Sen Gupta, Phys. Letters 28B, 480 (1969).

[3]E. H. Berkowitz, A. A. Rollefson, E. D. Berners, and C. P. Browne, Nucl. Phys. A140, 173 (1970).

[4]G. Hardie, R. E. Holland, L. Meyer-Schutzmeister, F. T. Kuchnir, and H. Ohnuma, Nucl. Phys. A134, 673 (1969).

[5]R. C. Bearse, D. H. Youngblood, and J. L. Yntema, Phys. Rev. 167, 1043 (1968).

[6]W. G. Davies, J. C. Harvey, and W. J. Darcey, Nucl. Phys. A128, 465 (1969).

[7]D. R. Goosman and D. E. Alburger, Phys. Rev. C 5, 1252 (1972).

[8]W. R. Harris, K. Nagatani, and J. W. Olness, Phys. Rev. C 2, 1412 (1970).

[9]B. W. Hooton, Nucl. Instr. Methods 27, 338 (1964).

[10]R. E. Chalmers, IEEE Trans. Nucl. Sci. 16, 132 (1969).

[11]A. R. Poletti and E. K. Warburton, Phys. Rev. 137, B595 (1965).

[12]D. H. Wilkinson, in *Nuclear Spectroscopy*, edited by F. Ajzenberg-Selove (Academic, New York, 1960), Part B, p. 862 ff.

[13]P. Wagner, J. P. Coffin, M. A. Ali, D. E. Alburger, and A. Gallmann, Phys. Rev. (to be published).

[14]B. H. Wildenthal, J. B. McGrory, E. C. Halbert, and H. D. Graber, Phys. Rev. C 4, 1708 (1971).

[15]A. R. Poletti, T. T. Bardin, J. G. Pronko, and R. E. McDonald, Phys. Rev. C 7, 1433 (1973).