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Properties of Levels in Cl^{34}

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22 levels of Cl^{34} below $E_x = 4.7$ MeV are populated by the γ-ray decay of the three resonances at $E_p = 1058$, 1098, and 1121 keV in the reaction $S^{33}(p,\gamma)Cl^{34}$. These resonances, selected for study because of their dominant modes of γ decay to levels above 2.7 MeV for which limited prior data exist, were investigated with an 80-cm^3 Ge(Li) detector, and with Ge(Li)-NaI coincidence and angular-correlation techniques. The results obtained for levels below 2.3 MeV are in general agreement with other recent work. A new result is a probable $J = 3$ assignment for the 2.180-MeV level. For higher-lying levels, γ-ray decay schemes and excitation energies with errors in the range from ±0.3 to ±2.3 keV were determined for 14 bound states in the range $2.3 < E_x < 4.7$ MeV and the three resonance levels. The reaction Q value was determined with the result $Q = 5139.9 \pm 0.9$ keV. The following J^π assignments (energies in MeV) result from the combination of the present work with a recent $S^{33}(He^3,d)Cl^{34}$ study: 2.72, 2^-; 3.55, 3^-; 3.60, $4^{(-)}$; 3.63, 5^-; 3.77, 1^-; 3.98, 3^-; 4.08, 4^-; 4.14, 2; 4.35, probably 1^-; 4.42, 1, 2, or 3; 4.51, probably 2^-; and 4.64, 2, 1, or 3. The resonance level assignments are $J^\pi(1058) = 3^{(-)}$, $J^\pi(1098) = 4^{(-)}$, and $J^\pi(1121) = 1^-$. It is shown that the three resonances are probably each odd-parity $T = 1$ levels. The probable shell-model configurations of some of the odd-parity levels are discussed.

INTRODUCTION

Very little experimental information on properties of energy levels of Cl^{34} was available until the marked increase in experimental interest which has occurred during the past two years. The theoretical importance of this self-conjugate odd-odd nucleus to an understanding of properties in the upper $2s$-$1d$ shell has been matched until recently by experimental difficulties associated with the relatively high level density. Most of this recent work has dealt with properties of levels below 3-MeV excitation. These studies include: the $S^{33}(p,\gamma)Cl^{34}$ decay-scheme and angular-correlation work by Graber and Harris;[1] the $S^{32}(He^3,p\gamma)Cl^{34}$ work from which branching ratios, spins and parities, and lifetimes have been obtained by Sykes[2] and by Brandolini, Engmann, and Signorini;[3] and accurate level energy measurements by Snover *et al.*[4] With this work, much detailed information including spin and parity assignments for all of the lowest six levels is now available.

Some progress has also been made in the determination of properties of higher-lying levels. Graber and Harris[1] examined several resonances in the reaction $S^{33}(p,\gamma)Cl^{34}$ with a 40-cm^3 Ge(Li) detector with considerable improvement over the results of older NaI(Tl) work.[5] Revised decay schemes for six resonance levels between $E_p = 1050$ and 1270 keV, and for 11 bound states below $E_x = 4$ MeV, were obtained. Unique spin assignments for two of the resonance levels and for the level at 2.376 MeV ($J = 4$) were obtained by $(p,\gamma\gamma)$ angular-correlation measurements. From another recent $S^{32}(He^3,p\gamma)Cl^{34}$ investigation, DeLuca, Lawson, and Chagnon[6] report $J = 1$ for the 2.581- and 3.126-MeV levels and $J = 2$ for the 2.722-MeV level. In older work, Dong-Hyok[7] studied the reaction S^{32}-

$(\alpha, d)Cl^{34}$ at $E_\alpha = 29$ MeV. Strong deuteron groups corresponding to levels at $E_x = 2.73$, 3.64, 4.06, 4.79, and 6.30 MeV were observed. Tentative J^π assignments of 2^-, 5^-, 3^-, and 4^- were proposed for the lowest four of these levels, and it was suggested that these levels belong to the $d_{3/2}f_{7/2}$ multiplet. Very recent and more definitive work by Erskine *et al.*,[8] who used the reaction $S^{33}(He^3, d)$-Cl^{34}, has provided detailed spectroscopic information on this multiplet, on the $d_{3/2}{}^2$ multiplet, and on other levels above $E_x = 3$ MeV. Their J^π assignments, especially for levels in the region $E_x = 2.7$–5.0 MeV, greatly aided the interpretation of the angular-correlation data obtained in the present $S^{33}(p, \gamma)Cl^{34}$ investigation.

The present contribution is primarily designed to provide more definitive data on higher-lying levels of Cl^{34}; in particular on odd-parity levels above 2.7 MeV which are presumed to have as major components $d_{3/2}f_{7/2}$ and $d_{3/2}p_{3/2}$. Prior to the work of Erskine *et al.*, no unambiguous experimental information was available on the parities of high-lying levels of Cl^{34}. In order to use the (p, γ) reaction to study the $T=0$ and $T=1$ members of the two-nucleon spectrum with $d_{3/2}f_{7/2}$ and $d_{3/2}p_{3/2}$ major components, one would preferably choose to study those resonances which decay by γ-ray cascades through lower levels with odd parity.

Graber and Harris pointed out that two of the (p, γ) resonances they studied (those at $E_p = 1058$ and 1098 keV) exhibited rather unusual γ-ray decay properties. These two resonance levels (plus a resonance at $E_p = 1121$ keV, studied in the older work by Glaudemans, Eriksson, and Werkhoven[5]) showed strong γ-ray branches to high-lying levels, in contrast to a more normal mode of decay favoring high-energy γ-ray transitions to lower-lying levels. This type of unusual decay pattern had been observed previously in P^{30} by Harris, Hyder, and Walinga[9] and in Ar^{38} by Engelbertink, Lindeman, and Jacobs.[10] In both of these referenced cases, the low-energy primary γ-ray transitions were shown to be $M1$ transitions between odd-parity levels of very similar configurations. The scope of the experimental work was therefore limited to an exhaustive study of the three resonance levels at $E_p = 1058$, 1098, and 1121 keV in the reaction $S^{33}(p, \gamma)Cl^{34}$, and of the bound levels in Cl^{34} through which these resonance levels decay. High-resolution γ-ray spectra were taken at each of the resonances and decay schemes were deduced. A series of γ-ray angular-distribution and, where necessary, $(p, \gamma\gamma)$ triple-correlation measurements were made to determine level spins.

GENERAL EXPERIMENTAL PROCEDURE

The reaction $S^{33}(p, \gamma)Cl^{34}$ was produced for most of this work by a beam of protons from the Aerospace Research Laboratories 2-MeV Van de Graaff accelerator. The beam resolution was approximately 1 keV. The water-cooled target was placed ~20 in. past the last aperature. The target was held in place against an O-ring surface on the end of the beam tube.

The targets were prepared by a procedure described by Watson.[11] A silver disk (0.625 in. diam ×0.01 in. thick) was soldered onto a 2-in.-diam ×0.125-in. brass disk. Elemental sulfur, enriched[12] to 83.5% in S^{33} was evaporated in air onto heated silver blanks allowing a thin layer of Ag_2S to be formed. The thickness of the target could

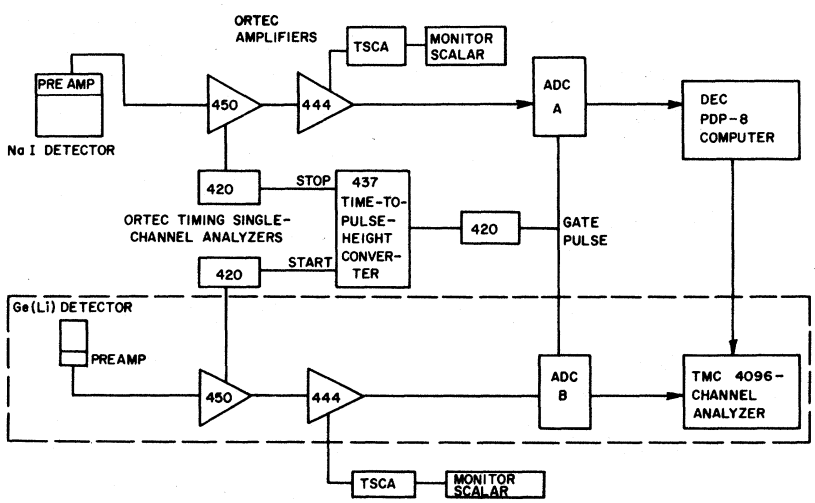

FIG. 1. Schematic diagram of the electronics used in the accumulation of the γ-ray angular-correlation data. The electronics enclosed in the dashed rectangle were used to accumulate γ-ray singles spectra.

be controlled by varying either the amount of sulfur evaporated or the time during which it was heated. Targets made in this way were quite durable, withstanding beam currents of 30 μA for many hours.

γ-ray spectra were taken at each of the three resonances at $E_p = 1058$, 1098, and 1121 keV. The spectra were observed by an 80-cm^3 Ge(Li) detector and were recorded by a 4096-channel pulse-height analyzer.

The measurements of resonance strengths, defined as $S = (2J+1)\Gamma_p\Gamma_\gamma/\Gamma$, followed the techniques described by Engelbertink and Endt.[13] A yield curve was measured in the neighborhood of each resonance energy, using a thin (~2 keV) S^{33} target enriched to 83.5% S^{33}. γ rays were detected using a 20.3-cm-diam × 20.3-cm-long NaI(Tl) detector placed at 55° relative to the proton beam direction.

In order to convert the relative strengths to absolute strengths, a comparison was made to the known strength,[13] $S = 21 \pm 3$ eV, of the $E_p = 1211$-keV resonance in the reaction $S^{34}(p,\gamma)Cl^{35}$. For this measurement a sulfur target of lower S^{33} isotopic abundance was used so that the S^{34} resonance could be observed. A sample of elemental sulfur composed of S^{32} (73.6%), S^{33}(22.1%), and S^{34} (4.2%) was used. The relative strength of the $E_p = 1211$-keV $[S^{34}(p,\gamma)Cl^{35}]$ and $E_p = 1098$-keV $[S^{33}(p,\gamma)Cl^{34}]$ resonance was measured to obtain the absolute strength of the S^{33} resonance. This absolute strength was then used to convert the relative strengths of the rest of the S^{33} resonances to absolute values.

Both $(p,\gamma\gamma)$ triple-correlation and (p,γ) angular-distribution measurements were performed with a 20.3-cm-diam × 20.3-cm-long NaI(Tl) detector and an 80-cm^3 Ge(Li) detector. Each detector was allowed to move in a horizontal plane containing the proton beam, target, and axis of symmetry of the other detector. Anisotropy corrections for each detector were determined as a function of detector angle using the known isotropic γ-ray transitions from the $E_p = 1160$-keV resonance in the reaction $C^{13}(p,\gamma)N^{14}$.

A schematic diagram of the data-handling electronics is shown in Fig. 1. Pulses from each detector were passed through preamplifiers into separate ORTEC model No. 450 research amplifiers. A fast bipolar output from each was sent to separate ORTEC model No. 420 timing single-channel analyzers (TSCA) to provide start and stop pulses for the model No. 437 time-to-pulse-height converter (TPHC). The stop pulse was delayed 0.5 μsec so that pulses in true coincidence corresponded to time intervals of 0.5 μsec in the spectrum from the TPHC. A differential discriminator with a window width of 300 nsec was set over the 0.5-μsec peak in the TPHC time spectrum to provide gating pulses for the analog-to-digital converters (ADC). While the fast bipolar outputs were generating logic signals for gating, the linear bipolar signals were additionally amplified and shaped by the ORTEC model No. 444 gated-biased amplifiers and then sent to the ADC units. A TSCA was also connected to each model No. 444 amplifier to provide a normalization monitor for measurements made at different detector angles. Digital addresses from ADC A [the ADC receiving signals from the NaI(Tl) detector] were sent to a PDP-8 computer, where they were compared with preset digital "windows." If the coincidence event was identified to be one of interest, routing instructions were sent to the analyzer to allow the spectrum from the Ge(Li) detector to be stored. Typically, four coincidence spectra were accumulated simultaneously, corresponding to Ge(Li) spectra of γ rays in coincidence with four regions of γ-ray energies measured by the NaI(Tl) detector system. Five-point correlations were measured by fixing the NaI(Tl) detector at 90° with respect to the proton-beam direction and by varying the Ge(Li) detector position through the angles 35, 55, 0, and 90°. With the Ge(Li) detector then fixed at 90°, the NaI(Tl) crystal was moved to 0° and the fifth point of the correlation measured. The process was then repeated in reverse order. With a beam current of 35 μA, about 30 min (the exact time was determined by the present monitor counts from the fixed detector) were required for each of the 5 points. Typically, 15 passes through each of the 5 points were needed to accumulate sufficient data. The process was greatly simplified when only angular distributions were being measured. The NaI(Tl) detector was fixed at $\theta = 90°$ and used only as a monitor. The electronics used for these measurements are shown within the dashed box of Fig. 1. Four-point angular-distribution measurements were made, i.e., Ge(Li) singles spectra were accumulated at $\theta = 0$, 35, 55, and 90°. From four to eight passes were required, depending on the strength of the resonance studied.

ANALYSIS AND RESULTS

The resonance proton energies were measured using a proton beam from the high-resolution insulated-core-transformer tandem accelerator. The beam energy was calibrated using the $E_p = 991.90 \pm 0.04$-keV resonance[14] in the $Al^{27}(p,\gamma)Si^{28}$ reaction. The S^{33} resonance energies found by this method are 1057.7 ± 0.5, 1097.7 ± 0.5, and 1120.8 ± 0.5 keV. When these results are combined with the fitted resonance excitation energies (given below), the Q value, 5139.9 ± 0.9 keV, for the reac-

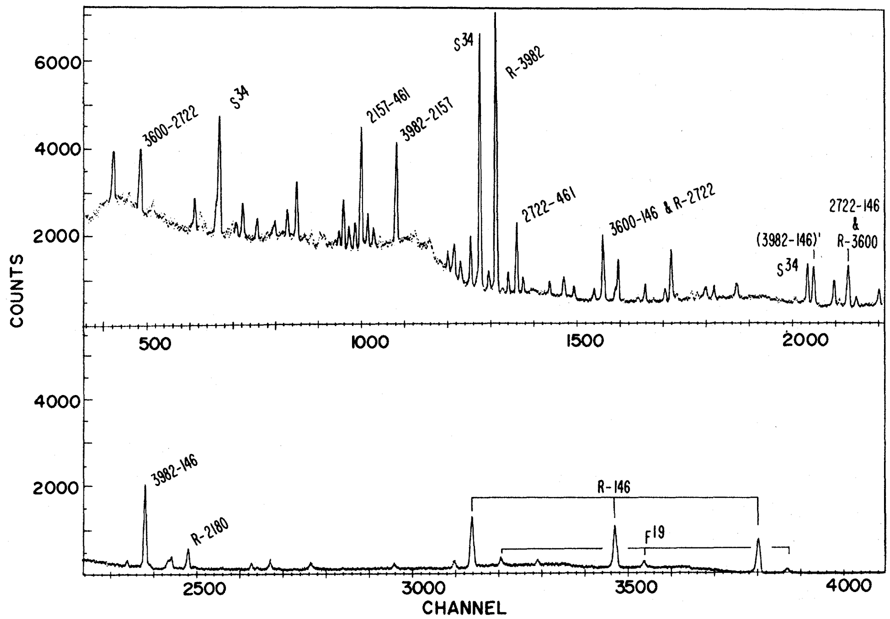

FIG. 2. Spectrum of γ rays at the $E_p = 1058$-keV resonance in the reaction $S^{33}(p,\gamma)Cl^{34}$. The data were obtained with an 80-cm^3 Ge(Li) detector.

tion $S^{33}(p,\gamma)Cl^{34}$ is obtained. This value is 15 ± 6 keV lower than the Q value given by Mattauch, Thiele, and Wapstra[15] and is in excellent agreement with the value of $Q = 5140.3 \pm 1.5$ keV found by Graber and Harris.[1]

The γ-ray spectra measured with the Ge(Li) detector 5 cm from the target are shown in Figs. 2, 3, and 4 for the resonances at $E_p = 1058$, 1098, and 1121 keV, respectively. Prominent transitions are indicated in each spectrum. The spectra taken at $\theta = 90°$ were used to extract γ-ray energies. Experimental γ-ray intensities measured at the four angles $\theta = 0$, 35, 55, and 90° were least-squares-fitted to a Legendre-polynomial expansion

$$W(\theta) = \sum_{\substack{K=0 \\ K \text{ even}}} A_K P_K(\cos\theta) . \qquad (1)$$

The best-fit intensities at $\theta = 55°$ were corrected for detector efficiency and, when necessary, for anisotropy and finite detector size. The γ-ray decay schemes were deduced from the singles spectra accumulated during the angular-distribution measurements and from coincidence spectra obtained in the angular-correlation measurements. Several γ-ray coincidence measurements were made independent of the angular correlations to resolve ambiguities in the decay schemes. The branching ratios for the decay of the three resonance levels and 21 bound excited states are summarized in Table I.

Several contaminant γ-ray peaks, with well-known energies, appear in one or more of the spectra. These include the beam-dependent γ rays at $E_\gamma = 1.632$ MeV [from the reaction $Na^{23}(p, \alpha\gamma)Ne^{20}$] and at $E_\gamma = 6.129$ MeV [$F^{19}(p, \alpha\gamma)O^{16}$], and the room background lines at $E_\gamma = 1.460$ MeV (K^{40}) and 2.613 MeV (ThC''). Snover *et al.*[4] recently reported accurate excitation energies for the first seven excited states of Cl^{34}. A combination of these γ-ray energies provided points within a given spectrum for a least-squares fit to a third-degree polynomial.

The excitation energies were determined by a least-squares fit to all transitions that were identified in spectra at each of the three resonances. The experimentally determined energies of γ rays identified as arising from transitions between any two levels were specified, while the excitation energies of the levels were the unknowns to be de-

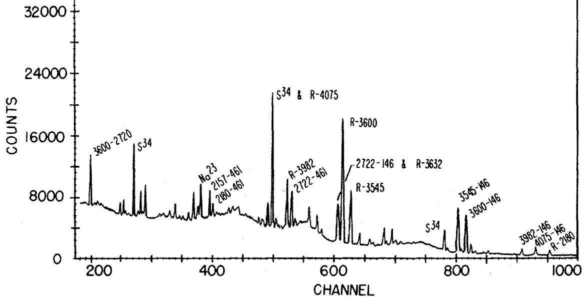

FIG. 3. Spectrum of γ rays at the $E_p = 1098$-keV resonance in the reaction $S^{33}(p,\gamma)Cl^{34}$. The data were obtained with an 80-cm^3 Ge(Li) detector.

termined. The ground-state energy and the excitation energies reported by Snover *et al.*[4] were added as constraint equations. The results of this calculation are presented in Table II.

The results of the strength measurements given in Table III are in reasonable agreement with the results of Graber and Harris,[1] except for the 1098-keV resonance. The discrepancies are traceable to the revised decay schemes used in the present analysis, and the advantage of highly enriched S^{33} targets used in this experiment. The difference between the present results and those obtained by Glaudemans, Eriksson, and Werkhoven[5] is not as easily explained. The strength values obtained by Glaudemans, Eriksson, and Werkhoven were based on the strength of the $E_p = 580$-keV resonance in $S^{32}(p,\gamma)Cl^{33}$, which was revised upward a factor of 1.5 by the work of Engelbertink and Endt.[13] A factor of about 4 still remaining is not understood.

The treatment of the angular-correlation theory as given by Harris, Hennecke, and Watson[16] was used in the analysis of the present γ-ray angular-correlation measurements. A discussion of the general analysis techniques in this formalism has been given elsewhere.[17] Several points peculiar to the present analysis are presented here.

For a two-step γ-ray cascade (Fig. 5), the angular-correlation function specifying the relative intensity $W(\theta_1, \theta_2, \varphi)$ can be written

$$W(\theta_1\theta_2\varphi) = \sum_{\substack{mMKN \\ L_1L_1'L_2L_2'}} P(m)\frac{\delta_1^{p_1}}{1+\delta_1^2} E_{KM}^N(J_1 L_1 L_1' J_2 m) \times Q_K Q_M H_M(\delta_2) X_{KM}^N(\theta_1\theta_2\varphi), \qquad (2)$$

where the primary and secondary γ rays are detected at angles θ_1 and θ_2, respectively, to the incident beam direction, and φ is the azimuthal angle between the detectors. The $Q_K Q_M$ are finite-geometry detector correction factors; δ_1 and δ_2 are the ratios of reduced matrix elements for L'-pole-to-L-pole radiation; and the exponent p_1, takes the values 0, 1, or 2 for pure L, mixed L-L', or pure L' radiation, respectively. The initial state is specified by the relative populations $P(m)$ of the various magnetic substates of J_1. Since the initial state is aligned, $P(m)$ is used to represent $P(m)+P(-m)$.

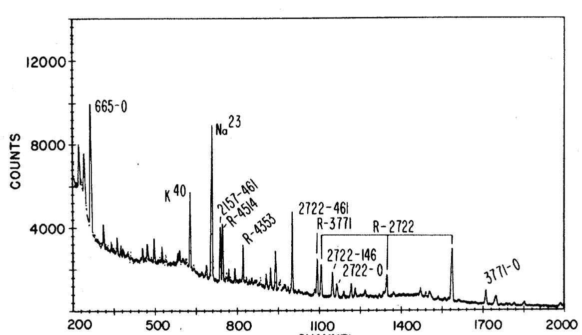

FIG. 4. Spectrum of γ rays at the $E_p = 1121$-keV resonance in the reaction $S^{33}(p,\gamma)Cl^{34}$. The data were obtained with an 80-cm^3 Ge(Li) detector.

The population parameters can be determined either from a knowledge of how the initial state was formed, or by treating them as additional parameters to be determined by a fit to the experimental data. This latter method may be successful when the number of magnetic substates populated is small, but in more unfavorable cases, because of the larger number of parameters, the method may not yield unambiguous solutions. The population parameters are expressed in terms of quantities characterizing the formation process in either of two representations as follows: In the channel-spin representation,

$$P(m) = \frac{1}{1+t}[P_{S_1}(m) + tP_{S_2}(m)],$$

where

$$P_{S_i}(m) = \frac{k^2}{1+\epsilon_i^2}[(S_i m J-m|l0)^2 + 2f\epsilon_i(S_i m J-m|l0) \times (S_i m J-m|l'0) + \epsilon_i^2(S_i m J-m|l'0)^2], \qquad (3)$$

and in the j_p representation,

$$P(m) = \sum_{m_s m_I}\left|\sum_{j_p}\left(\frac{2l+1}{2J+1}\right)^{1/2} \times (I m_I j_p m_s|Jm)(s m_s l0|j_p m_s)M(j_p)\right|^2. \qquad (4)$$

Both representations have been found to be useful in the present analysis.

The following conditions are valid in the present problem:

(1) Entrance channel spins $S_1 = 1$ and $S_2 = 2$ are possible; the channel-spin mixing t is defined as the intensity ratio $(S=2)/(S=1)$.

(2) Resonance spins J which would yield primary $E2$ or $M2$ strengths greater than 30 Weisskopf units (W.u.) are unreasonable.

(3) From considerations based upon the Wigner limit, $l \geq 4$ contributions are negligible.

(4) For each channel-spin S_i, the lowest two values of the orbital angular momentum l can contribute. The ratio of $l' = l+2$ to l contributions in each channel is denoted by ϵ_i.

(5) In the j_p representation, the incident-particle spin s is coupled to l to form j_p which in turn is coupled to the target spin I to obtain the resonance spin J.

TABLE I. γ-ray branching ratios (%) of resonance and bound levels of Cl^{34}.

Initial	Final state (MeV)																					
state (MeV)	0	0.15	0.46	0.67	1.23	1.89	2.16	2.18	2.38	2.61	2.72	3.55	3.60	3.63	3.77	3.98	4.08	4.14	4.35	4.42	4.51	4.64
6.226 [a]	0.8 ± 0.4		1 ± 0.5				5 ± 2				50 ± 6				13 ± 3			6 ± 2	8 ± 3	3 ± 1	11 ± 3	3 ± 1
6.206 [b]								4 ± 1				24 ± 6	49 ± 10	10 ± 5		6 ± 2	7 ± 4					
6.167 [c]		29 ± 7			3 ± 1	2 ± 1		5 ± 2		4 ± 2	8 ± 4	5 ± 2	7 ± 4			32 ± 6	5 ± 2	(5)				
4.639																						
4.514		16 ± 10		84 ± 10																		
4.416	100																					
4.353	100																					
4.137		72 ± 10					28 ± 10															
4.075		100							<15													
3.982		65 ± 6					26 ± 5				8 ± 4											
3.771	100																					
3.632		48 ± 7							52 ± 7													
3.601		48 ± 5							8 ± 4		44 ± 5											
3.545		100																				
2.722	13 ± 3	19 ± 3	47 ± 4	8 ± 3	3 ± 1	2 ± 1	8 ± 3															
2.611		45 ± 9		5 ± 4	50 ± 9																	
2.377		100																				
2.180		57 ± 8	28 ± 5	15 ± 7																		
2.158	13 ± 3	13 ± 6	67 ± 6	<1	7 ± 4																	
1.888		40 ± 4	60 ± 4																			
1.230 [d]		32 ± 5	36 ± 4	32 ± 4																		
0.666 [d]	93 ± 5	7 ± 5																				
0.461 [d]	100																					
0.146 [d]	100																					

[a] Resonance level at $E_p = 1121$ keV.
[b] Resonance level at $E_p = 1098$ keV.
[c] Resonance level at $E_p = 1058$ keV.
[d] Branching ratios taken from Refs. 2 and 3.

(6) The normalization factor k has the value $(2-\delta_{m,0})^{1/2}$ to account for the $m \geq 0$ restriction, and f is the Coulomb phase factor between incident protons of different l values.

The alignment of the initial state can also be specified in terms of the statistical tensors ρ_{k0} which are related to the population parameters by

$$\rho_{k0}=\sqrt{2J+1}\sum_m (-1)^{J-m}(JmJ-m|k0)P(m).$$

As Smith[18] has pointed out, the j_p representation eases the task of interpreting the configuration of the resonance state. The formalism is useful in a reciprocal way also. For specific assumptions concerning the configuration of the resonance state, the sets of allowed $P(m)$ over which the angular-correlation analysis should proceed can be limited.

Computer programs used in the analysis have been described by Hyder and Watson.[19] For an assumed spin sequence J_1, J_2, J_3 (see Fig. 5), the theoretical intensity $W^{\text{th}}(\theta_1, \theta_2, \varphi)$ is computed at discrete values of δ_1 and δ_2. At each point (δ_1, δ_2) a parameter χ^2 is computed. If each set of angles $(\theta_1, \theta_2, \varphi)$ is labeled by an index i, then

$$\chi^2=\frac{1}{N}\sum_i \frac{1}{w_i^2}(W_i^{\text{exp}}-W^{\text{th}})^2, \tag{5}$$

where N is the number of degrees of freedom, and w_i is the experimental error in the intensity. Values of δ_1, δ_2, $P(m)$, J_1, J_2, and J_3 for which χ^2 falls below the 0.1% confidence limit are retained as possible solutions. The χ^2 plots shown below were obtained by projecting the shadow of the χ^2 surface onto the δ_1, δ_2 axes.

In the remainder of this section arguments necessary for establishing level spins are summarized. The angular-distribution data are presented in Table III in the form of coefficients of the Legendre-polynomial expansion of Eq. (1). The coefficients are normalized with respect to the intensity coefficient A_0. No A_4 terms statistically different from zero were observed.

TABLE II. Excitation energies of bound levels in Cl^{34}.

Present work [a] E_x (keV)	Graber and Harris [b] E_x (keV)
146.36 ±0.03	146.8 ±1.0
461.00 ±0.04	461.5 ±0.3
665.55 ±0.05	664.6 ±0.3
1230.24 ±0.07	1228.8 ±0.7
1888.1 ±0.8	1885.9 ±1.6
2157.98 ±0.05	2158.4 ±1.2
2180.5 ±0.6	
2377.3 ±1.2	2375.6 ±0.7
2611.2 ±1.3	
2721.7 ±0.3	2720.4 ±1.6
3545.3 ±0.6	3544.6 ±1.3
3600.7 ±0.4	3598.4 ±1.2
3632.5 ±1.4	
3771.0 ±0.7	
3982.1 ±0.3	3982.0 ±1.1
4075.4 ±0.9	
4136.6 ±1.2	
4352.7 ±0.9	
4415.8 ±2.3	
4514.5 ±0.7	
4639.0 ±2.3	

[a] Excitation energy measurements of the first seven excitated states by Snover *et al.* (Ref. 4) were added as constraints in the present least-squares determination of level energies.

[b] Reference 1.

Resonance Levels

E_p=1098 keV

This resonance level was observed to decay to levels at 3.63 and 3.98 MeV for which J^π assignments of 5^- and 3^-, respectively, had been made by Erskine *et al.*[8] For assumed resonance spins of $J_R=5$ and 3, $E2$ transition strengths of 130 W.u. $(R\rightarrow 3.98)$ and 90 W.u. $(R\rightarrow 3.63)$ are obtained. These strengths are much larger than the values considered reasonable, so the resonance spin is assigned as $J_R=4$. The correlation analysis at this resonance was insensitive to the choice of $P(m)$ values.

E_p=1058 keV

This resonance level was observed to decay to the 3.982-MeV level (30%) and to the 4.075-MeV level (5%) for which J^π assignments of 3^- and 4^-, respectively, have been made.[8] For the assumed spin sequences $(5\rightarrow 3^-)$ and $(2\rightarrow 4^-)$, $E2$ transition strengths of 420 and 140 W.u., respectively, would be needed. Neither $J_R=3$ nor $J_R=4$ can be eliminated by strength arguments. Analysis of primary and secondary angular-distribution results for the $R\rightarrow 3.982\rightarrow 0.146$ cascade for the spin sequence $4\rightarrow 3\rightarrow 3$ yields a solution for $\arctan\delta_1 \geq 15°$ for all values of $P(m)$ obtained from Eq. (4). Such a primary quadrupole mixing ratio would imply an unreasonably high $E2$ strength of 40 W.u. The resonance spin is thus unambiguously determined as $J_R=3$. Rather than search through all possible sets of $P(m)$ consistent with this assignment, an alternate analysis was made using the statistical tensors. As pointed out by Harris, Hennecke, and Watson,[16] if the primary γ ray is

TABLE III. Angular-distribution coefficients. Corrections for anisotropy and finite detector solid angle are included. R stands for resonance level.

E_p (keV)	Transitions (E_x in MeV)	$J^\pi_i \to J^\pi_f$	a_2
1058	$R \to 0.146$	$3^{(-)} \to 3^+$	$+0.28 \pm 0.03$
	$R \to 1.230$	$3^{(-)} \to 2^+$	-0.24 ± 0.10
	$R \to 1.888$	$3^{(-)} \to 2^+$	-0.21 ± 0.12
	$R \to 2.180$	$3^{(-)} \to (3^+)$	$+0.28 \pm 0.07$
	$R \to 2.611$	$3^{(-)} \to ?$	$+0.10 \pm 0.10$
	$R \to 3.545$	$3^{(-)} \to 3^-$	$+0.28 \pm 0.05$
	$R \to 3.982$	$3^{(-)} \to 3^-$	$+0.25 \pm 0.03$
	$R \to 4.075$	$3^{(-)} \to 4^-$	-0.12 ± 0.05
	$3.982 \to 2.157$	$3^- \to 2^+$	-0.20 ± 0.03
	$3.982 \to 0.146$	$3^- \to 3^+$	$+0.21 \pm 0.03$
	$3.601 \to 2.722$	$4^{(-)} \to 2^-$	$+0.24 \pm 0.06$
	$3.545 \to 0.146$	$3^- \to 3^+$	$+0.23 \pm 0.08$
	$2.722 \to 0$	$2^- \to 0^+$	$+0.26 \pm 0.13$
	$2.722 \to 0.666$	$2^- \to 1^+$	-0.20 ± 0.04
	$2.180 \to 0.146$	$(3^+) \to 3^+$	-0.02 ± 0.06
	$2.180 \to 0.461$	$(3^+) \to 1^+$	$+0.03 \pm 0.12$
	$2.158 \to 0.461$	$2^+ \to 1^+$	-0.20 ± 0.03
1098	$R \to 2.180$	$4^{(-)} \to (3^+)$	-0.24 ± 0.07
	$R \to 3.545$	$4^{(-)} \to 3^-$	-0.22 ± 0.02
	$R \to 3.601$	$4^{(-)} \to 4^{(-)}$	$+0.31 \pm 0.01$
	$4.075 \to 0.146$	$4^- \to 3^+$	-0.07 ± 0.05
	$3.982 \to 0.146$	$3^- \to 3^+$	$+0.00 \pm 0.05$
	$3.632 \to 2.377$	$5^- \to 4^+$	-0.24 ± 0.05
	$3.632 \to 0.146$	$5^- \to 3^+$	$+0.21 \pm 0.07$
	$3.601 \to 2.722$	$4^{(-)} \to 2^-$	$+0.25 \pm 0.01$
	$3.601 \to 2.378$	$4^{(-)} \to 4^+$	-0.14 ± 0.07
	$3.601 \to 0.146$	$4^{(-)} \to 3^+$	-0.13 ± 0.02
	$3.545 \to 0.146$	$3^- \to 3^+$	$+0.25 \pm 0.02$
	$2.722 \to 0$	$2^- \to 0^+$	$+0.21 \pm 0.09$
	$2.722 \to 0.461$	$2^- \to 1^+$	-0.17 ± 0.04
1121	$R \to 2.157$	$1^- \to 2^+$	-0.13 ± 0.10
	$R \to 2.722$	$1^- \to 2^-$	$+0.01 \pm 0.05$
	$R \to 3.771$	$1^- \to 1^-$	-0.23 ± 0.03
	$R \to 4.137$	$1^- \to 2$	$+0.01 \pm 0.09$
	$R \to 4.352$	$1^- \to (1^-)$	-0.24 ± 0.05
	$R \to 4.416$	$1^- \to ?$	$(+0.32 \pm 0.16)$
	$R \to 4.514$	$1^- \to (2^-)$	$+0.05 \pm 0.03$
	$R \to 4.639$	$1^- \to ?$	-0.18 ± 0.15
	$4.514 \to 0.146$	$(2^-) \to 3^+$	-0.10 ± 0.20
	$4.514 \to 0.666$	$(2^-) \to 1^+$	-0.00 ± 0.08
	$4.352 \to 0$	$(1^-) \to 0$	-0.16 ± 0.08
	$4.137 \to 0.146$	$2 \to 3^+$	$+0.20 \pm 0.20$
	$3.771 \to 0$	$1^- \to 0^+$	-0.20 ± 0.05
	$2.722 \to 0$	$2^- \to 0^+$	-0.20 ± 0.06
	$2.722 \to 0.146$	$2^- \to 3^+$	$+0.07 \pm 0.05$
	$2.722 \to 0.461$	$2^- \to 1^+$	$+0.11 \pm 0.03$
	$2.722 \to 0.666$	$2^- \to 1^+$	-0.04 ± 0.11
	$2.722 \to 1.230$	$2^- \to 2^+$	-0.07 ± 0.21
	$2.722 \to 1.888$	$2^- \to 2^+$	$+0.1 \pm 0.3$
	$2.157 \to 0.461$	$2^+ \to 1^+$	$+0.03 \pm 0.04$

pure dipole, the highest-order statistical tensor allowed is ρ_{20}. Since any primary mixing appreciably different from zero is inconsistent with reasonable $E2$ strengths, ρ_{20} can be calculated for several strong primary transitions by setting $\delta_1 = 0$. Within the errors, these primary angular distributions yield the value $\rho_{20} = -0.62 \pm 0.04$.

A set of $P(m)$ consistent with this value of ρ_{20} was then used in the analysis of the angular-distribution data. A typical example of the result of this analysis is seen in Fig. 6. The $(R \to 0.146)$ primary angular distribution is considered for a $(3 \to 3)$ spin sequence. The solid line through the experimental points is the theoretical fit for a $J_R = 3$ and $\delta_1 = 0$ assignment. The χ^2 vs δ_1 projection curve is also shown. The conclusion is $J_R(E_p = 1058 \text{ keV}) = 3$.

$E_p = 1121$ keV

The presence of nonisotropic γ-ray angular distributions eliminates $J_R = 0$. The $J_R = 3$ possibility is exlcuded by the 13% branch to the 3.771-MeV level [assigned (1^-) by Erskine *et al.*[8]] which would require an $E2$ strength of 65 W.u.

Preliminary proton elastic scattering measurements at the $E_p = 1121$-keV resonance were consis-

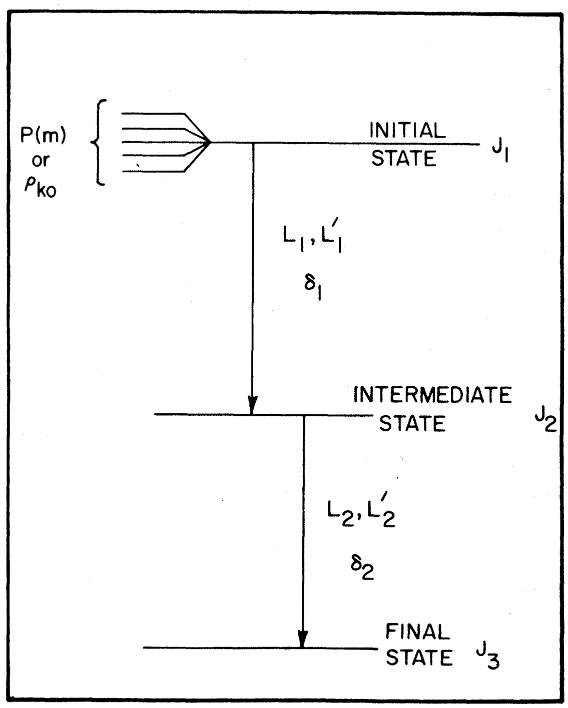

FIG. 5. Double γ-ray cascade. The alignment of the initial state of total angular momentum J_1 is specified either by the set of population parameters $P(m)$ or by the set of statistical-tensor parameters ρ_{k0}. The primary (secondary) γ ray is of mixed multipolarities L_1 and L_1' (L_2 and L_2') with mixing amplitude δ_1 (δ_2).

tent with p-wave capture. Angular-distribution data on the $R\to 2.722\to 0.461$, $R\to 2.722\to 0.146$, and and $R\to 3.771\to 0$ cascades were sufficient to exclude $J_R=2$. The $P(m)$ for this case were calculated for pure $l=1$ capture. This latter assumption is not unreasonable because of the high relative penetrability of $l=1$ compared with $l=3$ protons at 1.1 MeV, and because of the small value ($f=-0.03$) of the Coulomb phase factor appearing in the $(l=3)/(l=1)$ interference term. The γ-ray angular distributions were analyzed for $J_R=1$ in the statistical-tensor formalism under the assumption that the primary multipolarity mixing ratios were zero. The several values of ρ_{20} obtained this way were in agreement within errors with a weighted average of $\rho_{20}=0.58\pm 0.05$. A set of population parameters consistent with this value of ρ_{20} was used in subsequent analyses. As an example, the results of the angular-distribution measurements for the $R\to 2.722\to 0$ cascade are shown in Fig. 7. The conclusion is $J_R(E_p=1121\text{ keV})=1^{(-)}$.

A summary of the above results for the resonance levels is given in Table IV.

Bound Levels

Several levels of particular interest are discussed in the remainder of this section. These levels include both those for which spin assignments were made in the present work and those determined by the work of Erskine *et al.*[8]

4.639 MeV

A level at 4.636 MeV was observed by Erskine *et al.* and assigned $J^\pi=(0^-)$. In the present study a level at 4.639 ± 0.002 MeV was found to be fed by a 3% branch from the $E_p=1121$-keV resonance level. The angular distribution of the 1.588-MeV primary γ ray was measured with the result $A_2=-0.17\pm 0.14$, while a $(1^-\to 0^-)$ sequence for the pure dipole $R\to 4.639$ transition would result in a theoretical value $A_2=+0.45$. Thus $J(4.639)=0$ can be excluded. The observed angular distribution is consistent with $J=1$ or 2 for the 4.639-MeV level.

4.353 MeV

This level is excited only at the $E_p=1121$-keV resonance. Its spin has not previously been reported although Erskine *et al.* assigned it odd parity. The level was observed to decay only to the ground state. Angular-distribution measurements of both the primary and secondary members of the $R\to 4.353\to 0$ cascade yield results consistent with $J=1$ for the 4.353-MeV level. Although this assignment is not exclusive, the similarity between this cascade and the $R\to 3.771\to 0$ cascade (see discussion of 3.771-MeV level below) supports this assignment. The conclusion is $J(4.353)=(1)^-$.

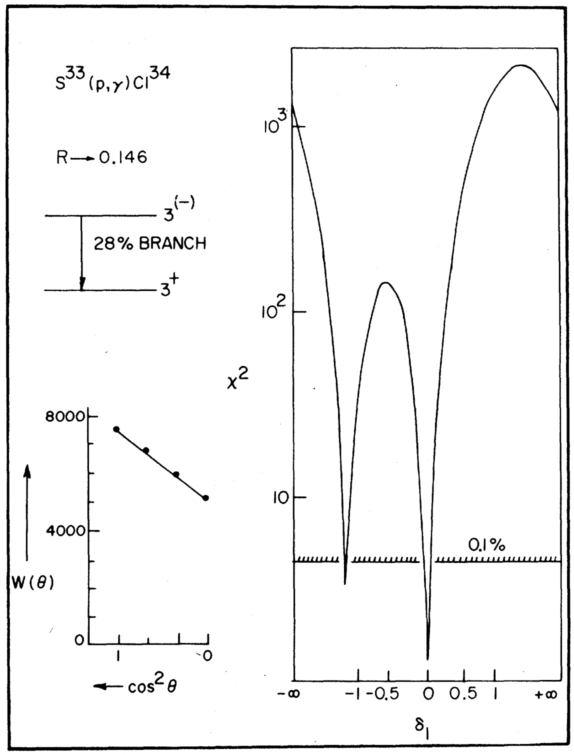

FIG. 6. Measured angular distribution and χ^2 versus δ_1 curve for the $R\to 0.146$ cascade at the $E_p=1058$-keV resonance. The solid line through the data points represents the best fit for $J(R)=3$, and the population parameters given in Table III.

4.137 MeV

This level also is fed only by the $E_p=1121$-keV resonance. A level at 4.143 MeV was observed by

TABLE IV. Summary of experimental results for resonance levels.

E_p (keV)	E_x (keV)	$\frac{(2J+1)\Gamma_p\Gamma_\gamma}{\Gamma}$ (eV)	J^π	Population parameters $P(0)$	$P(1)$	$P(2)$
1057.7 ± 0.5	6166.9 ± 0.8	2.8 ± 0.9	$3^{(-)}$	0.262	0.439	0.322
1097.7 ± 0.5	6206.3 ± 1.2	3.1 ± 0.9	$4^{(-)}$	0.089	0.378	0.533
1120.8 ± 0.5	6226.5 ± 1.0	1.9 ± 0.6	1^-	0.061	0.939	···

Erskine *et al.* and was assigned $J^\pi = 3^-(2^-)$ in text, but as 2^+, $T=1$ in a "note added in proof." The level observed in the (p,γ) work decayed to both the 0.146-MeV level ($J^\pi = 3^+$) and the 2.158-MeV level ($J^\pi = 2^+$). The angular distributions of both γ rays in the $R \to 4.137 \to 0.146$ cascade are isotropic, a result consistent with a $J(4.137) = (2 \text{ or } 3)$ assignment. The possibility $J(4.137)=3$ implies a primary $E2$ strength of 220 W.u. and therefore can be eliminated. The conclusion is $J(4.137)=2$.

4.075 and 3.982 MeV

Both of these levels are fed at the $E_p = 1058$- and 1098-keV resonances. Erskine *et al.* have made unambiguous assignments of $J^\pi(4.075) = 4^-$ and $J^\pi(3.982) = 3^-$. The upper level was observed in the present work to decay primarily to the first excited state. There is a possibility of a 4.075 $\to$ 2.377 transition [$J^\pi(2.377) = 4^+$] but the transition, if present, is weak and obscured by the $2.158 \to 0.461$ decay. The 3.982-MeV level was observed to decay to the levels at 0.146 MeV ($J^\pi = 3^+$), 2.158 MeV ($J^\pi = 2^+$), and 2.722 MeV ($J^\pi = 2^-$). The angular-distribution measurements yielded results in agreement with those of Erskine *et al.* The conclusions are $J^\pi(4.075) = 4^-$ and $J^\pi(3.982) = 3^-$.

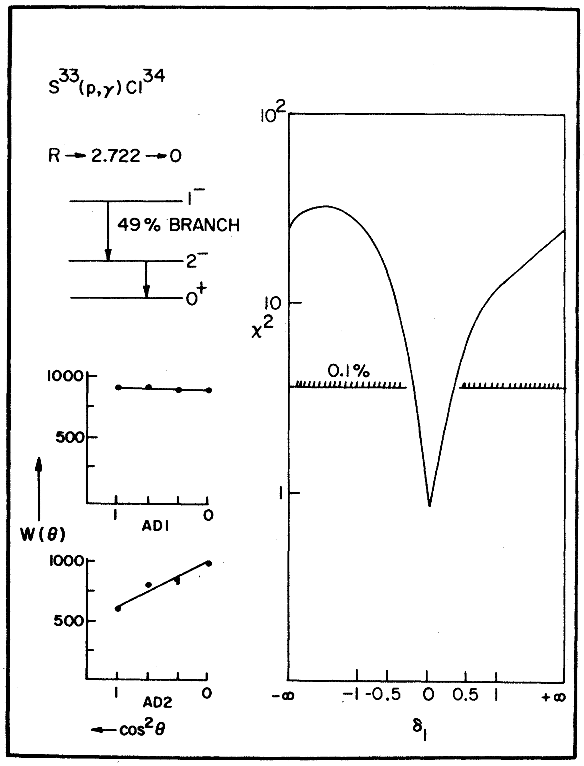

FIG. 7. Measured angular distributions and χ^2 versus δ_1 curve for the $R \to 2.722 \to 0$ γ-ray cascade at the $E_p = 1121$-keV resonance. The solid line through the data points represents the best-fit curve for $J(R)=1$ and $J(2.722)=2$, and the population parameters given in Table III.

3.771 MeV

The 3.771-MeV level was assigned $J^\pi = (1^-)$ by Erskine *et al.* This level was populated by a 13% branch from the $E_p = 1121$-keV resonance level, and was observed to decay entirely to the ground state. The angular-distribution results for the $R \to 3.771 \to 0$ cascade are shown in Fig. 8. The conclusion is $J^\pi(3.771) = 1^{(-)}$

3.601 and 2.722 MeV

These levels are discussed together because of a 0.878-MeV quadrupole transition observed between them. The 3.601-MeV level was not observed in the work of Erskine *et al.* They assigned $J^\pi = 2^-$ to the 2.772-MeV level; a result confirmed in the present investigation.

The 3.601-MeV level decays with branches to the 0.146-, 2.377-, and 2.722-MeV levels, while the 2.722-MeV level decays with observed branches to each of the first seven levels of Cl^{34}. The spin of the 3.601-MeV level has been assigned $J = 4$ by angular-correlation measurements at the $E_p = 1098$-keV resonance. The results of angular correlations on the $3.601 \to 2.722 \to 0.461$ cascade are shown in Fig. 9. With the population parameters of the resonance level and the γ-ray multipolarity mixing ratio of the $R \to 3.601$ transition fixed by the other correlation information, the population parameters of the 3.601-MeV level were calculated. The angular correlation shown in the figure excludes $J(3.601) = 3$. The conclusions are $J(3.601) = 4$ and $J^\pi(2.722) = 2^-$.

3.545 MeV

This level was assigned $J = (2, 3)^-$ by Erskine *et al.* It was excited in this investigation by direct branches from both the $E_p = 1058$- and 1098-keV resonances, and was observed to decay only to the 0.146-MeV level. The spin of this level was determined to be $J = 3$ from angular-correlation measurements at the $E_p = 1098$-keV resonance. These results are presented in Fig. 10. The conclusion is $J^\pi(3.545) = 3^-$.

2.180 MeV

The 2.180-MeV level was populated at the 1058-keV resonance (5% branch) and the 1098-keV resonance (4% branch). The level was observed to decay with branches to the 0.146-, 0.461-, and 0.666-MeV levels in agreement with the results of Brandolini, Engmann, and Signorini[3] who assigned the level $J^\pi = (1^+, 2, 3^+)$, $T=0$. The $J=1$ assignment is eliminated, since the primary from the 1098-keV resonance level ($J=4$) would require an $E3$ strength of 10^4 W.u. The $J(2.180)=(3)$ assignment is consistent with observed angular distributions (see Table III) of the $R\rightarrow 2.180$ transitions from both resonance levels. The conclusion is $J^\pi(2.180) = (3^+)$.

SUMMARY OF EXPERIMENTAL RESULTS

The aim of this study was to obtain information on the properties of excited states of Cl^{34}, especially the odd-parity states, by means of the reaction $S^{33}(p,\gamma)Cl^{34}$. The results of previous and concurrent investigations complemented, and in some cases overlapped, this work. In most instances where comparisons could be made, the agreement was quite good. Notable exceptions occurred in the decay of the resonance levels and some lower-lying levels where the large volume Ge(Li) detector available to this work made possible the identification of several weak, previously unobserved, transitions.

In those cases where the (p,γ) reaction provided independent determinations of level spins, identical conclusions were generally obtained. Conflicting results were limited to the 4.639-MeV level which was tentatively assigned 0^- in Ref. 8 but was shown to have $J=1$, 2, or less probably 3, in the present work. The 3.601-MeV level, not observed in the (He^3, d) work, was assigned $J=4$ from the (p,γ) angular correlations.

A probable assignment of $J=3$ was obtained for the 2.180-MeV level. Otherwise, no special attempt was made in this study to reexamine previously reported spins of even-parity states below $E_x = 2.7$ MeV. Sufficient information on these states had already been given in the several recent experimental papers referenced. Those results consistent among these prior studies were assumed in this analysis. No evidence for γ-ray transitions from or to a level at $E_x = 1.924$ MeV reported by Erskine *et al.*[8] was observed.

A summary of the branching ratios, spins, parities, and excitation energies of the 25 Cl^{34} levels observed in this work is given in Tables I and II and Fig. 11. The multipolarity mixing ratios extracted from the correlation data are given in Table V. The branching ratios of the first four excited states were not well determined in the (p,γ) reaction, and so the values quoted are as reported by Sykes[2] and Brandolini, Engmann, and Signorini.[3]

The probable parity of the 3.60-MeV level, not observed in the (He^3, d) work of Erskine *et al.*, can be established from the decay-scheme and angular-correlation results. This level ($J=4$) decays to the 2.72-MeV level ($J^\pi = 2^-$, 44% branch) and to the 0.146-MeV level ($J^\pi = 3^+$, 48% branch). If the pari-

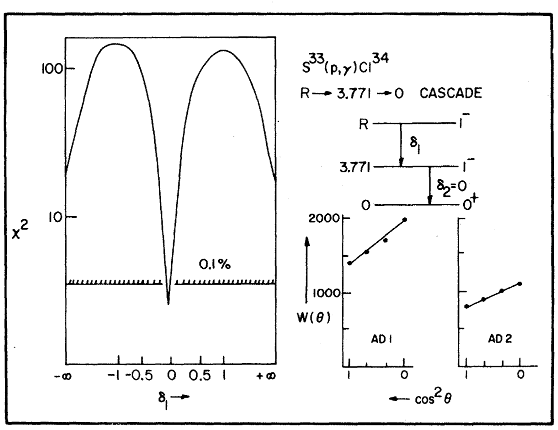

FIG. 8. Measured angular distribution and χ^2 versus δ_1 curve for the $R\rightarrow 3.771\rightarrow 0$ γ-ray cascade at the $E_p = 1121$-keV resonance. The solid line through the data points represents the best-fit curve for $J(R)=1$, $J(3.771)=1$, and the population parameters given in Table III.

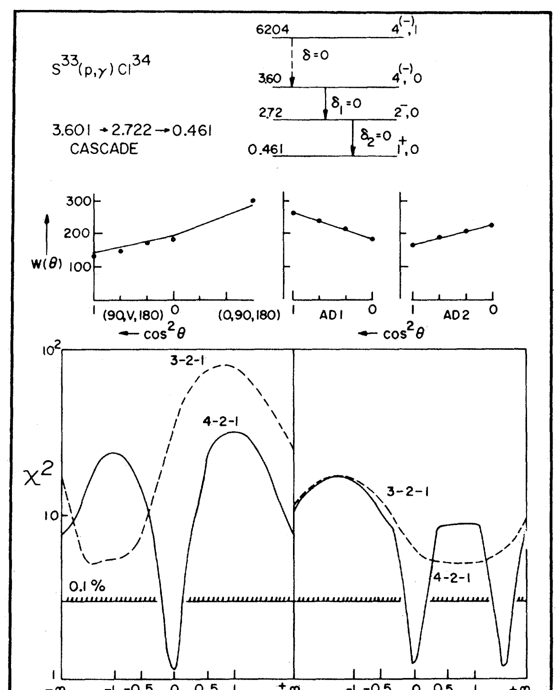

FIG. 9. Measured angular correlations, angular distributions, and χ^2 projection curves for the $3.601\rightarrow 2.722 \rightarrow 0.461$ γ-ray cascade at the $E_p = 1098$-keV resonance. The population parameters for the 3.601-MeV level were calculated using the $P(m)$ values of the resonance level (see Table III) and the multipolarity mixing ratio $\delta(R\rightarrow 3.601) = 0$ deduced from other correlation data obtained at this resonance. The solid lines through the data points represent the best-fit curve for $J(3.601) = 4$.

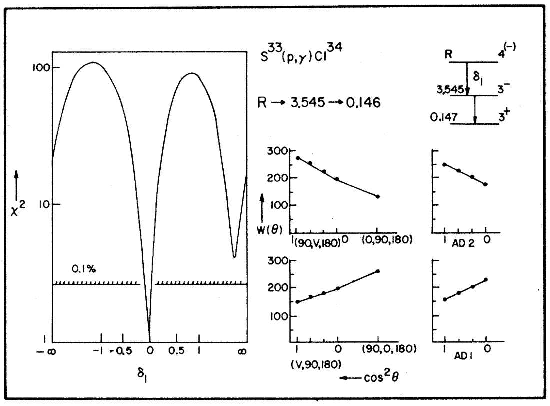

FIG. 10. Measured angular correlations, angular distributions, and χ^2 versus δ_1 curve for the $R \to 3.545 \to 0.146$ γ-ray cascade at the $E_p = 1098$-keV resonance. The solid lines through the data points represent the best-fit curve for $J(R)=4$, $J(3.545)=3$, and the resonance population parameters given in Table III.

ty is assumed to be even, then an $M2$ strength as large as 10 W.u. for the $3.60 \to 2.72$ transition would imply $|M|^2(M1) \leq 2\times10^{-6}$ W.u. and $|M|^2(E2) \leq 2\times10^{-4}$ W.u. for the $3.60 \to 0.146$ transition. The $M1$ and $E2$ strengths, calculated using the $\delta(3.60 \to 0.146) \leq 0.18$ multipolarity mixing ratio from the present angular-correlation results, are very much lower than values typically observed in this mass region.

If, however, the 3.60-MeV level parity is assumed odd, a similar calculation yields the quite reasonable values $|M|^2(E1) \leq 2\times10^{-6}$ W.u. and $|M|^2(M2) \leq 0.2$ W.u. for the $E1$ and $M2$ strengths of the $3.60 \to 0.146$ γ-ray transition. The $E1$ strength obtained for the odd-parity assumption is consistent with the inhibition of $E1$ γ-ray transitions with $\Delta T = 0$ in self-conjugate nuclei, and perhaps more importantly, consistent with the probable configurations of the two levels. The 0.146-MeV level is known to be predominantly an $s_{1/2}{}^4 d_{3/2}{}^2$ configuration, and if the 3.60-MeV level consists primarily of configurations of the type $s_{1/2}{}^n d_{3/2}{}^m f_{7/2}$, an electric dipole transition would be j forbidden. Odd parity for this level, although regarded as very probable, should be confirmed by other measurements before accepted as certain.

TABLE V. Multipolarity mixing ratios.

Transition (E_x in MeV)	$J^\pi_i \to J^\pi_f$	δ
6.167 [a] → 0.146	$3^{(-)} \to 3^+$	$+0.02 \pm 0.03$
6.167 [a] → 1.230	$3^{(-)} \to 2^+$	0.0 ± 0.01
6.167 [a] → 3.982	$3^{(-)} \to 3^-$	0.05 ± 0.06 or -1.3 ± 0.2
6.167 [a] → 4.075	$3^{(-)} \to 4^-$	-0.03 ± 0.05 or >7
6.206 [b] → 3.545	$4^{(-)} \to 3^-$	0.0 ± 0.02
6.206 [b] → 3.601	$4^{(-)} \to 4^{(-)}$	$+0.03 \pm 0.05$
6.226 [c] → 2.722	$1^- \to 2^-$	$+0.05 \pm 0.05$
6.226 [c] → 3.771	$1^- \to 1^-$	-0.03 ± 0.05
3.601 → 2.722	$4^{(-)} \to 2^-$	-0.01 ± 0.04
3.601 → 0.146	$4^{(-)} \to 3^+$	-0.07 ± 0.04
3.545 → 0.146	$3^- \to 3^+$	$+0.06 \pm 0.05$
2.722 → 0.461	$2^- \to 1^+$	$+0.03 \pm 0.05$ or $+2.3 \pm 0.5$

[a] Resonance level at $E_p = 1058$ keV.
[b] Resonance level at $E_p = 1098$ keV.
[c] Resonance level at $E_p = 1121$ keV.

DISCUSSION

The number of odd-parity states in Fig. 11 is clearly greater than that expected if only the $d_{3/2}f_{7/2}$ spectrum were observed. Members of the $d_{3/2}p_{3/2}$ spectrum are probably present, together with states arising from one and two holes in the $2s_{1/2}$ shell coupled to particles in the $d_{3/2}$, $f_{7/2}$, and $p_{3/2}$ shells.

The $l=3$ spectroscopic strength deduced from the (He^3, d) study by Erskine *et al.*[8] was observed to be divided among the levels at $E_x = 2.722$, 3.633, 3.982, and 4.075 MeV. These levels were identified as the $J^\pi = 2^-$, 5^-, 3^-, and 4^- states of the $T=0$, $d_{3/2}f_{7/2}$ spectrum. The spins of these levels are consistent with the present (p,γ) data.

The two levels at $E_x = 3.545$ and 3.601 MeV have been assigned $J=3$ and 4, respectively, from our

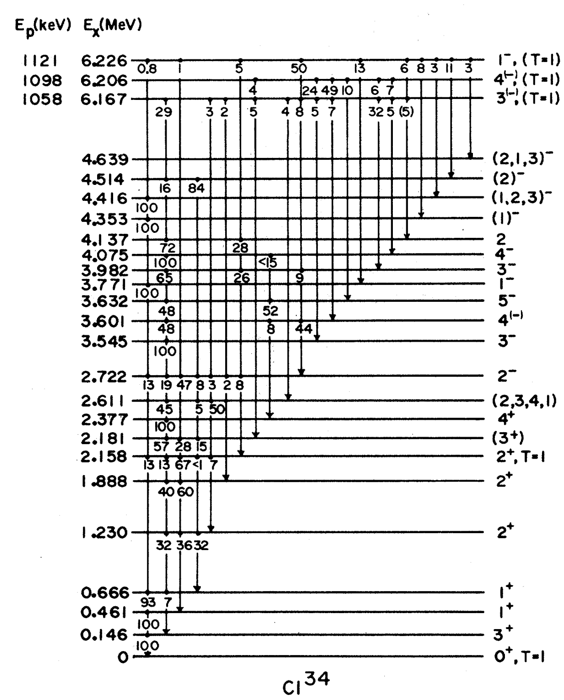

FIG. 11. Decay schemes of the resonance and bound levels of Cl^{34} as observed in the present work. Branching ratios of the first four excited states are taken from Refs. 2 and 3. Errors on branching ratios are given in Table I.

angular-correlation measurements. The 3.545-MeV level was observed by Erskine *et al.* to be formed by $l=1$ transfer; the 3.601-MeV level was not observed in the (He^3, d) work, implying that these states do not have a strong $d_{3/2}f_{7/2}$ character. The 3.545- and 3.601-MeV levels are fed strongly at the $E_p=1098$-keV resonance (branching ratios 24 and 49%, respectively), but comparatively weakly at the $E_p=1058$-keV resonance (branching ratios 6 and 8%, respectively). This behavior suggests that the 1098-keV resonance level is probably not primarily of the type $d_{3/2}f_{7/2}$, $T=1$.

The 1058-keV resonance level, however, does show a strong (31%) branch to the 3.982-MeV level. In addition, the resonance level decays to the 2.722- and 4.075-MeV levels which were observed by Erskine *et al.* to have strong $l=3$ strength. This behavior suggests that this resonance level might be the $(J^\pi, T)=(3^-, 1)$ member of the $d_{3/2}f_{7/2}$ spectrum.

The unusual γ-ray decay of the three resonance levels to high-lying odd-parity levels resembles the $M1$ decay schemes of odd-parity analog levels observed in neighboring nuclei.[9,10] With the parity of the 1058- and 1098-keV resonance levels tak-

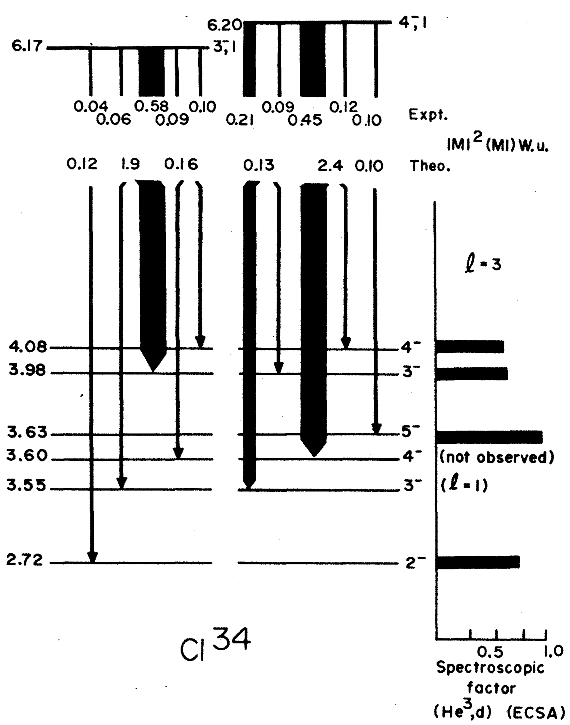

FIG. 12. Experimental and theoretical values of the $M1$ transition strengths for the resonances at $E_p=1058$ and 1098 keV. The theoretical $M1$ strengths were calculated for $\Delta T=1$ transitions between states of pure $d_{3/2}f_{7/2}$ configurations. The $l=3$ spectroscopic factors are from Ref. 8.

en to be odd, the experimental $M1$ transition strengths of primary transitions to the odd-parity levels are as shown in Fig. 12. The spectroscopic factors given in the figure are from Erskine *et al.*

Prosser and Harris[20] have obtained an analytic expression for the absolute $M1$ strengths for $\Delta T=1$ transitions between states of pure $d_{3/2}{}^n f_{7/2}$ configurations. Such a matrix element for $n=1$ can be expressed as

$$\langle d_{3/2}f_{7/2}\Gamma|\,\Omega_0^{\bar{L}}(M1)\,|d_{3/2}f_{7/2}\Gamma'\rangle$$
$$=\sum_r (-1)^{T-M_T+r}\begin{pmatrix} T & r & T' \\ -M_T & 0 & M_T\end{pmatrix}\times\left(A^r\langle d\|\Omega^{(r)}(M1)\|d\rangle + B^r\langle f\|\Omega^{(r)}(M1)\|f\rangle\right),$$

where Γ and Γ' stand for the J, T couplings of the $d_{3/2}$ and $f_{7/2}$ nucleons in the initial and final states. The coefficients A^r and B^r are given in direct-product notation by

$$A^r=(-1)^{\Gamma'+\bar{L}}\hat{\Gamma}\hat{\Gamma}'\begin{Bmatrix} d & d & \bar{L} \\ \Gamma' & \Gamma & f\end{Bmatrix},$$

and

$$B^r=(-)^{\Gamma+\bar{L}}\,\hat{\Gamma}\hat{\Gamma}'\begin{Bmatrix} f & f & \bar{L} \\ \Gamma' & \Gamma & d\end{Bmatrix},$$

where $\hat{\alpha}\equiv(2J_\alpha+1)^{1/2}\times(2T_\alpha+1)^{1/2}$, $\bar{L}\equiv(L,r)$, and the bracketed symbols stand for the products of spin and isospin 6-j coefficients. The reduced single-nucleon matrix elements can be written as

$$\langle d\|\Omega^{(r)}(M1)\|d\rangle=\tfrac{1}{5}\sqrt{30}\sqrt{2r+1}\,\beta_{nm}(3-\tfrac{1}{2}g_s^r),$$

and

$$\langle f\|\Omega^{(r)}(M1)\|f\rangle=\tfrac{6}{7}\sqrt{7}\,\sqrt{2r+1}\,\beta_{nm}(3+\tfrac{1}{2}g_s^r),$$

where β_{nm} is the nuclear magneton and $g_s^r\equiv g_s^p+(-1)^r g_s^n$ and g_s^p (g_s^n) is the gyromagnetic ratio of the proton (neutron). The absolute $M1$ radiative width is

$$\Gamma(M1)=\frac{4k^3}{3(2J+1)}\,|\langle d_{3/2}f_{7/2}\Gamma|\,\Omega_0^{\bar{L}}(M1)\,|d_{3/2}f_{7/2}\Gamma'\rangle|^2,$$

where $k\equiv E_\gamma/\hbar c$. The theoretical $M1$ strengths obtained from this expression, together with the experimental results, are given in Fig. 12. The agreement is reasonable for the 6.17-MeV resonance level ($E_p=1058$ keV), suggesting a rather pure $d_{3/2}f_{7/2}$ configuration. This is not the case for the 6.20-MeV level ($E_p=1098$ keV), since most of the $M1$ strength arises from transitions to levels that are not predominant $d_{3/2}f_{7/2}$ character as indicated by the spectroscopic factors in Fig. 12.

The analysis in the statistical-tensor formalism of angular-distribution data at the $E_p=1058$-keV resonance yielded a value $\rho_{20}=-0.62\pm0.04$. An expression for the statistical tensor in terms of the channel-spin and orbital mixings, given by Nordhagen,[21] was used to compute a lower bound on the $(l=3)/(l=1)$ mixing. The result, $|\epsilon|\geqslant 0.36$, implies, when f-wave and p-wave relative penetrabilities are taken into account, that the ratio of $(l=3)/(l=1)$ reduced widths is greater than or equal to 5.7. This indication that the resonance level has strong f-wave character is consistent with the $M1$ strength results discussed above.

The 1121-keV resonance level ($E_x=6.226$ MeV) was assigned $J=1$ from angular-correlation measurements of the $R\rightarrow 3.771\rightarrow 0$, and $R\rightarrow 2.722\rightarrow 0.462$ cascade transitions. The parity ($\pi=-$) for the resonance level is assigned from preliminary results of elastic proton scattering measurements performed during this investigation. The energy of this level is consistent with its identification as the analog of the 6.349-MeV (1^-, $T=1$) level in S^{34}.[22]

γ-ray multipolarity mixing ratios of several transitions between even-parity states in Cl^{34} are known. For example, Graber and Harris[1] have reported $\delta(2.377\rightarrow 0.146)=-6.3\pm^{2.0}_{3.2}$, and Brandolini, Engmann, and Signorini[3] found $\delta(1.887\rightarrow 0.146)=1.2\pm 0.8$, and $\delta(1.230\rightarrow 0.146)=2.2\pm 1.8$. The mixing ratios of several transitions between odd-parity levels were found in this work to be near zero (see Table V). The large $E2/M1$ mixing ratios in the even-parity examples are expected from the wave functions for these states given by Glaudemans, Weichers, and Brussaard[23] and Wildenthal.[24] The 0.146-MeV level wave function has a major component of the type s^4d^2, while the other level wave functions have a significant component of the type s^3d^3. An $M1$ single-particle transition between states of these types would require l-forbidden transitions from the d to the s orbits. Since the $E2$ transition is not forbidden, the large $E2/M1$ mixing ratios are possible. In the odd-parity case, however, the $M1$ transitions occur between states of similar configurations (e.g., $df\rightarrow df$, or $dp\rightarrow dp$), and no large $E2$ admixtures are expected.

Sona, Schrieder, and Kutschera[25] have reported the results of lifetime measurements on the 4.632- and 4.688-MeV levels in S^{34}. The 4.632-MeV level had previously been assigned $J^\pi=3^-$ by Hinds.[22] Sona, Schrieder, and Kutschera deduced the $E1$ strengths of the 4.632 $(3^-)\rightarrow 2.127$ (2^+) and 4.632 $(3^-)\rightarrow 3.304$ (2^+) transitions and compared them to theoretical values based on wave functions obtained from shell-model calculations with an inert S^{32} core. The calculated $E1$ strengths are factors of 2 and 10 larger than experimental values for the $4.632\rightarrow 3.304$ and $4.632\rightarrow 2.127$ transitions, respectively. They suggest the possibility of describing the 4.632-MeV level in terms of simple shell-model configurations. One would expect to observe the analog of this 3^- state in Cl^{34} at about 4.6 MeV. No level with $E_x>4.2$ MeV was observed by Erskine *et al.* to be formed by $l=3$ transfer, so it is reasonable to conclude that this 3^- level is not a member of the $d_{3/2}f_{7/2}$ spectrum. They suggest that the 3^- state in S^{34} is a collective state, similar possibly to the case in Ca^{40} in which the lowest 3^- state shows a reduced transition probability $B(E3)$ to the 0^+ ground state much larger than expected from a single-particle state. No state which could be identified with the analog of 3^- level in S^{34} was seen in the present experiment; Erskine *et al.* have observed several states around $E_x\approx 4.6$ MeV formed by $l=1$ transfer.

The existence of the $J^\pi=3^-$ ($E_x=3.545$ MeV) and $4^{(-)}$ ($E_x=3.601$ MeV) states below the 3^- and 4^- states ($E_x=3.982$ and 4.075 MeV, respectively) with major $d_{3/2}f_{7/2}$ components was not expected. Neither of the lower-energy levels was observed to have $l=3$ strength in the (He^3, d) work of Erskine *et al.* A tentative description of these states is possible from preliminary results of shell-model calculations on odd-parity states of $A=34$ nuclei being performed in connection with the present study. An inert Si^{28} core is assumed in these calculations, and the configuration space includes $s_{1/2}{}^n d_{3/2}{}^m f_{7/2}$ and $s_{1/2}{}^n d_{3/2}{}^m p_{3/2}$, with the restrictions $n+m=5$ and $n\geqslant 2$. The residual interaction used in the initial calculations is of the modified surface δ type (MSDI). These calculations reproduce the general features of these 3^- and 4^- states and indicate that the lowest J^π, $T=3^-$, 0 level has a major component of the type $s_{1/2}{}^4 d_{3/2} p_{3/2}$, and the lowest 4^-, 0 state has a major component of the type $s_{1/2}{}^3 d_{3/2}{}^2 f_{7/2}$. Such states would appear weakly in $l=3$ transfer as observed. The 3^-, 0 and 4^-, 0 levels which appear at slightly higher excitation energy in the calculation have major components $s_{1/2}{}^4 d_{3/2} f_{7/2}$ in agreement with the experimentally strong $l=3$ transfer to these states.

Interesting $M2$ transitions are observed in the decay of the 2.722-MeV level (2^-) to the ground state (0^+), and the 3.632-MeV level (5^-) to the (3^+) level at 0.146 MeV. The strengths of these $M2$ transitions can be calculated[20] for assumed wave functions of the states involved. The latter transition should be nearly pure isoscalar ($\Delta T=0$) and the former nearly pure isovector ($\Delta T=1$), since Cl^{34} is self-conjugate. In order to obtain estimates of the strengths of these transitions, we have assumed that the 2^- and 5^- levels are pure two-nucleon $d_{3/2}f_{7/2}$, $T=0$ states, and have taken the wave functions for the 0^+, $T=1$ and 3^+, $T=0$ levels from the calculations of Wildenthal *et al.*[24] The $M2$ strengths in Weisskopf units then obtained are 2.2 W.u. for the $2^-\rightarrow 0^+$ $\Delta T=1$ transition and 0.09 W.u. for the $5^-\rightarrow 3^+$ $\Delta T=0$ transition. These results imply mean lifetimes of 1.6 and 43 psec, respectively, for the 2^- and 5^- levels after the appropriate correction for relative branching ratios. It can be expected that departures from pure $d_{3/2}f_{7/2}$ configuration for the 2^- and 5^- levels will lead to $M2$ strengths smaller than these estimates and thus to longer lifetimes. Experimental determination of these lifetimes would be a valuable aid in understanding the true nature of these levels.

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