PHYSICAL REVIEW VOLUME 164, NUMBER 4 20 DECEMBER 1967

Properties of Some Levels of Cl^{35}

P. TARAS,* L. W. OLEKSIUK, R. E. AZUMA, AND J. D. PRENTICE
University of Toronto, Toronto, Canada
(Received 31 May 1967)

Angular distributions, triple angular correlations, and polarizations of the γ rays emitted in the reaction $S^{34}(p,\gamma)Cl^{35}$ have been measured. Three resonances were investigated at proton energies of 1.020, 1.213, and 1.513 MeV. Spin and parity assignments for the 1.220-, 3.006-, 3.163-, 4.174-, 7.358-, 7.544-, and 7.841-MeV levels are discussed. The following spin-parity assignments are deduced: 3.163 MeV, $\frac{7}{2}^-$; 7.358 MeV, $\frac{3}{2}$; 7.544 MeV, $\frac{7}{2}^-$; 7.841 MeV, $\frac{3}{2}$.

I. INTRODUCTION

THIS paper reports experiments performed to measure some spins, parities, and multipole mixing ratios for levels and γ-ray transitions in Cl^{35}.

The energies of the levels up to 4.2 MeV have been measured by Endt *et al.*[1] by inelastic proton scattering on Cl.[35] Many levels above 7 MeV have been found as resonances in the $S^{34}(p,\gamma)Cl^{35}$ reaction, by Antufyev *et* al.[2] who also established the spins of some resonance levels by measuring the angular distributions of the decay γ rays. The first two exited states at 1.220 and 1.762 MeV have been assigned positive parity, on the basis of the *ft* values for the decay of Ar^{35}.[3] A comprehensive study of the γ ray emitted in the decay of nine resonances of the $S^{34}(p,\gamma)Cl^{35}$ reaction, in the proton energy range 0.756–1.214-MeV, by Hazewindus *et al.*[4] has revealed two further levels at 5.03 and 5.22 MeV and has provided the γ-ray branching ratios for most of the low-lying levels. These and other experimental data on Cl^{35} have been reviewed by Endt and Van der Leun.[5] The published data concerning the levels is briefly summarized in Fig. 1. Gamma-ray branching ratios for the decays of some of these levels are given in Table XII of Ref. 4.

Since the completion of the experiments reported here two theses, by Hazewindus[6] and by Watson,[7] have become available. These report experiments similar to our own on the 4.38-MeV and 3.16-MeV γ ray cascades from the 7.544-MeV level. Our results differ from theirs in some respects and detailed comparison will be made in Sec. III. Hazewindus[6] has also measured the angular distribution of some other γ rays from which he deduced the spins of some resonance levels and assigned tentative spins for some of the low-lying states. His results are incorporated in Fig. 1.

In the present work measurements were performed on the γ rays from the three resonances of the $S^{34}(p,\gamma)Cl^{35}$ reaction populated by protons of 1.020, 1.213 and 1.513 MeV.

For the first resonance, the branching ratios for the γ-ray decay via various intermediate states from the resonance level were obtained. The following angular distributions were also measured: (p,γ) angular dis-

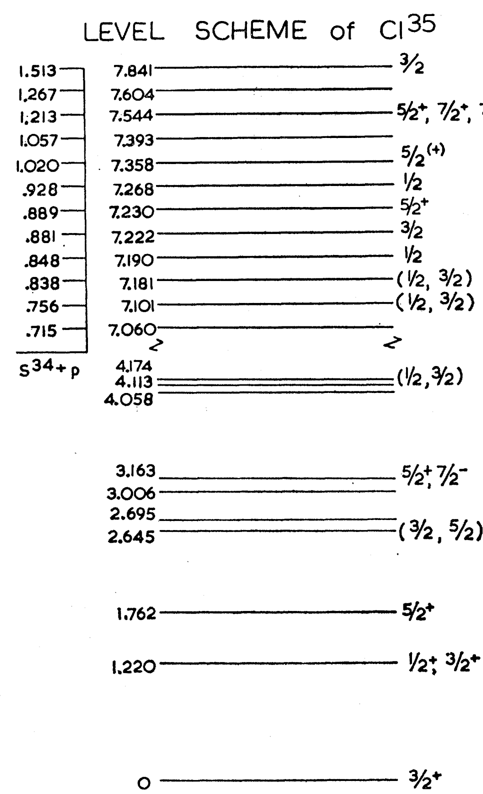

FIG. 1. Summary of the information on the energy levels, spins, and parities of Cl^{35} prior to this work. Two levels at 5.03 and 5.22 MeV are not shown. The energies are given in MeV. The spins and parities in parentheses are considered as tentative assignments. The scale on the left-hand side of the figure shows the proton energies required to form the resonance levels in Cl^{35} by the $S^{34}(p,\gamma)Cl^{35}$ reaction.

* Permanent address: Département de Physique, Université de Montréal, Montréal, Canada.

1 P. M. Endt, C. H. Paris, A. Sperduto, and W. W. Buechner, Phys. Rev. **103**, 961 (1956).

2 P. Antufyev, A. K. Valter, V. Gonchar, E. Kopanesz, A. W. Lvov, and S. Szitko, Izv. Akad. Nauk SSSR Ser. Fiz. **24**, 877 (1960); **25**, 265 (1961).

3 O. C. Kistner, A. Schwarzschild, and B. M. Rustad, Phys. Rev. **104**, 154 (1956).

4 N. Hazewindus, W. Lourens, A. Scheepmaker, and A. H. Wapstra, Physica **29**, 681 (1963).

5 P. M. Endt and C. Van der Leun, Nucl. Phys. 34, 1 (1962).

6 N. Hazewindus, thesis, Technische Hogeschool, Delft Drukkerij Pasmans, 1964 (unpublished).

7 D. D. Watson, thesis, University of Kansas, 1965 (unpublished); Phys. Letters **22**, 183 (1966).

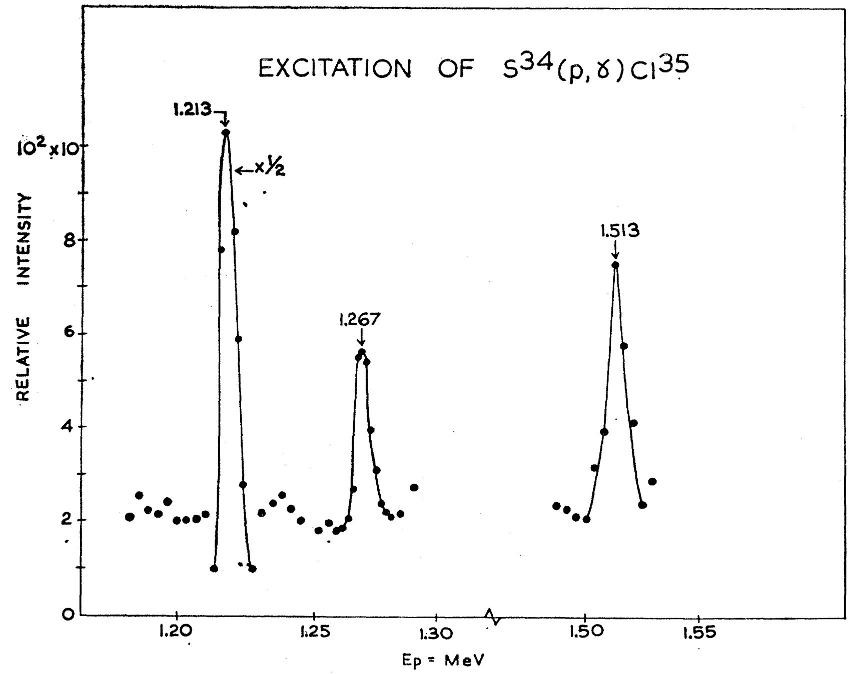

FIG. 2. The γ-ray yield curve as a function of proton bombarding energy for $E_\gamma > 1.5$ MeV in the region of the resonances studied in this work.

tributions, i.e., the angular distributions of the γ rays from the resonance level, relative to the proton direction; and $(p,x\gamma)$ angular distributions, i.e., the angular distributions of the second γ ray of a cascade with respect to the proton direction, but with the intermediate γ ray, x, unobserved. The resulting spin assignments are in agreement with those of Hazewindus.[6]

The second resonance at $E_p = 1.213$ MeV, has an excitation energy of 7.544 MeV and decays almost entirely to the level at 3.163 MeV. This latter level then decays to the ground state with a relative intensity of 94%.[8] The measurements made for this cascade were (p,γ) and $(p,x\gamma)$ angular distributions, $(p,\gamma_{12}\gamma_2)$ triple angular correlations, where γ_{12} is the primary γ ray of the cascade and γ_2 is the secondary γ ray and linear polarization measurements for the 4.38-MeV primary and 3.16-MeV secondary γ rays.

For the $E_p = 1.513$-MeV resonance, (p,γ), $(p,x\gamma)$, and $(p,\gamma_{12}\gamma_2)$ angular-correlation measurements were performed. The branching ratios were deduced from the ungated and coincidence γ-ray spectra.

TABLE I. Dimensions of NaI(Tl) crystal γ-ray spectrometers referred to in the text.

NaI(Tl) Crystal No.	Diameter (cm)	Length (cm)
1	4.4	5.1
2	7.6	7.6
3	12.7	10.2
4	12.7	10.2

[8] W. Wiesehahn (private communication).

In the next section, the experimental apparatus and techniques are briefly described. Section III contains the experimental results and a description of the data reduction, and Sec. IV, a discussion of the spin and parity assignments and of other properties of the nucleus.

II. EXPERIMENTAL PROCEDURES

A. General

The proton beam from the 3-MeV Van de Graaff accelerator of the Ontario Cancer Institute was momentum-analyzed in a 25° bending magnet and brought to a focus at the target. The beam energy spread could be limited to ± 2 keV and relative proton energies were known to this accuracy. The field of the analyzing magnet was monitored with a nuclear-magnetic-resonance probe and an energy calibration was performed by observing the 872.5- and 1347-keV resonances of the $F^{19}(p,\alpha\gamma)O^{16}$ reaction.

The targets were CdS evaporated onto 0.013-cm-thick metal foils. Those used in the earlier experiments, supplied by the isotope separation division of the United Kingdom Atomic Energy Authority, contained sulfur enriched to 46% in S^{34} and were on nickel backings; later targets were made in this laboratory from CdS containing sulfur enriched to 37% in S^{34} and evaporated onto gold backings.

In order to locate the resonances to be studied, a partial γ ray yield curve was measured. Gamma rays of energy greater than 1.5 MeV were detected in a 7.6-cm diameter by 7.6-cm long NaI(Tl) scintillation spectrometer. The yield as a function of proton energy in

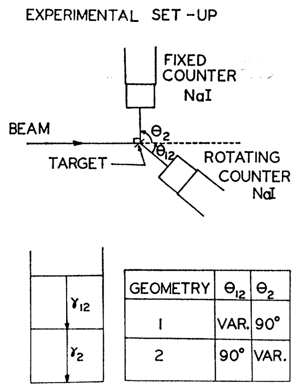

FIG. 3. Schematic drawing of the experimental arrangement of the scintillation counters and target in the case of triple angular-correlation measurements. The fixed counter was placed at 90° with respect to the proton beam direction while the rotating counter could be moved between 0° and 90°. Both counters are in the horizontal plane. The appropriate angles and "geometries" are also defined. In geometry 1, the first γ ray of a cascade, γ_{12} was detected in the rotating counter in coincidence with the second γ ray of that cascade, γ_2, which was detected in the fixed counter and vice versa for geometry 2.

the region of the upper two resonances used in this experiment is shown in Fig. 2. The resonance energies are seen to agree well with those of Ref. 2.

The γ-ray measurements were made with various combinations of the four cylindrical NaI(Tl) scintillation spectrometers whose dimensions are listed in Table I. All the crystals were mounted on Dumont photomultipliers by the Harshaw Chemical Company.

Pulses from the photomultipliers were amplified in double delay line amplifiers. A fast-slow coincidence arrangement was used when necessary. The fast resolving time obtainable was $2\tau = 60$ nsec. In some of the runs, a longer resolving time was used to ensure constant efficiency. Pulse-height spectra were recorded in both a 512-channel and a 1024-channel Nuclear Data pulse-height analyzer. The possibility of dividing each of the analyzer memories into sections permitted the concurrent recording of several pulse-height spectra from one run.

The relative intensities of the various γ rays from each resonance were deduced from the ungated spectra and from sum coincidence spectra.[9,10] The spectrometers were calibrated with standard spectra from Y^{88} and Na^{24} sources and with the 7.48-MeV gamma rays from the $Be^9(p,\gamma)B^{10}$ reaction.

B. Angular-Distribution Measurements

The (p,γ) and $(p,x\gamma)$ angular distributions were obtained by measuring the intensity of the appropriate γ rays in spectrometer No. 2 (see Table I) at a series of angles in the horizontal plane, normalized to the number of γ-rays detected in spectrometer No. 3 placed at 90° to the beam. The cylindrical target chamber was mechanically fixed at the center of an accurately machined steel table which carried the carriages for the spectrometers and their associated lead shielding. Each of the carriages was fixed to a rigid radial arm attached to a central pivot which was coaxial with the target chamber. The angular distribution table was machined to tolerances of ± 0.025 cm and was optically aligned with the target and the analyzing slits for the proton beam. Any possible remaining systematic errors were searched for by comparing the same angular distribution measured on both sides of the beam and at angles of less than and greater than 90° to the proton beam direction. No such errors were detected and any error thus introduced was negligible compared to the errors quoted in the experimental results.

C. Triple Correlations

Triple correlation measurements of the type discussed by Ferguson and Rutledge[11] were made with the same angular-distribution table but using crystals No. 3 and No. 4. The beam current was limited to less than 1.5 μA to allow the use of targets with thin backings and indirect cooling, thus simplifying the corrections for the absorption of γ rays in the target backing. The crystals were placed with their front faces 20 cm from the target for the 1.213-MeV resonance and a counting time of about 20 h was then required at each angle. The smaller yield at the 1.513-MeV resonance, together with the need to examine some weak branches of the decay, made it necessary to advance the crystals to 10 cm from the target and to count for about 40 h at each angle. One crystal was kept fixed at 90° to the beam in the horizontal plane and the other crystal was moved

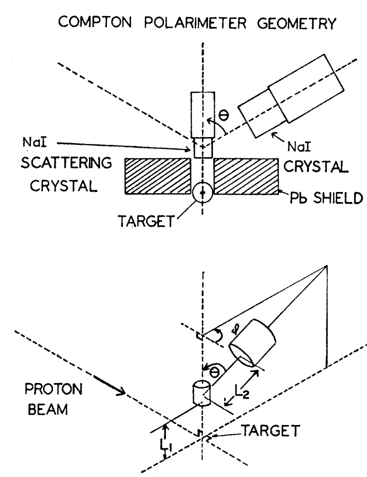

FIG. 4. Schematic drawing showing the Compton polarimeter and the relevant angles which are described in the text.

[9] A. M. Hoogenboom, Nucl. Instr. Methods 3, 57 (1958).
[10] J. E. Draper and A. A. Fleischer, Nucl. Instr. Methods 9, 67 (1960).
[11] A. J. Ferguson and A. R. Rutledge, Atomic Energy of Canada Report No. AECL-420, 1957 (unpublished).

TABLE II. γ-ray intensities from 7.358-MeV level.

γ-ray energy (MeV)	Transition to level at: (MeV)	Observed relative intensity % Present work	Ref. 4
7.36	0	15±8	18±4
6.14	1.22	70±18	67±14
5.60	1.76	15±8	10±3
3.30	4.06	≤10	5±2

to positions between 0° and 90° in the horizontal plane. The sum-coincidence method was used in the triple correlation measurements because it offered the following advantages: (1) Simple spectra resulted, in which only a total energy peak appeared for each γ ray together with a low background outside the peak region; (2) correlations for all two γ-ray cascades, between the resonance level and the ground state, were obtained simultaneously; (3) correlations for two geometries, for each cascade, were measured concurrently in each run.

The geometries shown in Fig. 3, can be described by θ_{12}, the angle between the primary γ ray and the proton beam; θ_2, the angle between the secondary γ ray and the proton beam; and ϕ, the angle between the vectors $\mathbf{p}(\text{proton})\times\mathbf{p}(\gamma_{12})$ and $\mathbf{p}(\text{proton})\times\mathbf{p}(\gamma_2)$. The two geometries used can thus be specified by $(\theta_{12},\theta_2,\phi)$ and will be referred to as geometry 1 (variable 0 to 90°, −90°, 180°) and geometry 2 (−90°, variable 0 to 90°, 180°). The intensity in the full energy peaks of the sum-coincidence spectrum was measured at a series of angles and normalized to the number of counts in the ungated spectrum from the fixed crystal. Frequent observations of this ungated spectrum showed that there was no significant change in the γ-ray background during the run. Periodic checks were also made of the setting of the sum coincidence gate. Two runs were taken for each correlation and the sequence of angles was varied between runs, to minimize any systematic errors due to long-term drifts. The agreement between corresponding runs was, in each case, within the expected statistical fluctuations.

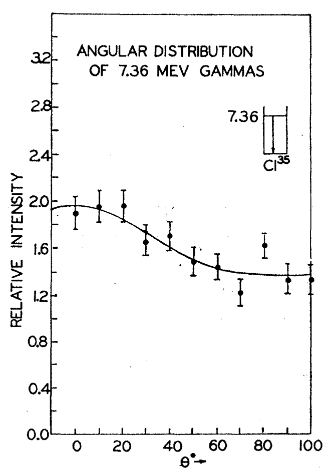

FIG. 5. The angular distribution of the 7.36-MeV γ rays from the level populated at $E_p=1.020$ MeV. The solid curve is a least-squares fit to the experimental data.

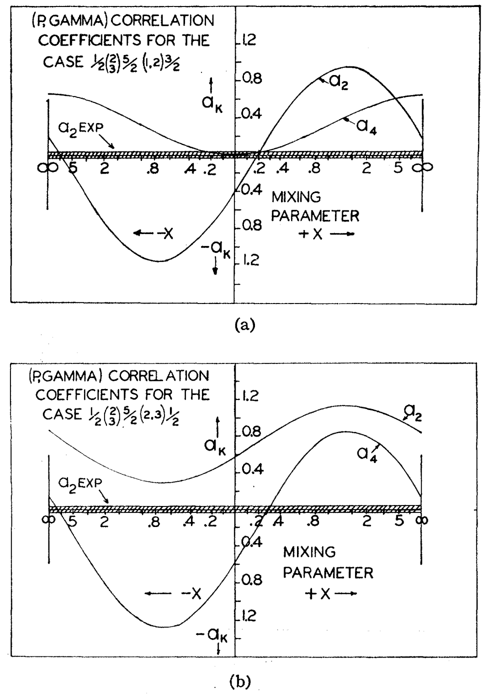

FIG. 6. The theoretical (p,γ) angular-distribution coefficients as a function of the multipole mixing parameter, x, for the spin sequences (a) $\frac{5}{2}\rightarrow\frac{3}{2}$ and (b) $\frac{5}{2}\rightarrow\frac{1}{2}$ with an entrance channel spin of $\frac{1}{2}$ and possible values of 2 or 3 for the orbital angular momentum of the bombarding protons. The experimental value of the a_2 coefficient obtained from the distribution of the 6.14-MeV γ rays emitted between the 7.36-MeV level and the 1.22-MeV level is also shown.

D. Polarization Measurements

The linear polarizations of the 4.38- and 3.16-MeV γ rays, occurring in the decay of the 7.544-MeV level, were measured with a Compton polarimeter utilizing crystals No. 1 and No. 2. The former was fixed above the target to receive γ rays emitted at 90° to the proton beam. Gamma rays that were Compton scattered by crystal No. 1 were detected in crystal No. 2 which was shielded by 7.5 cm of lead from direct radiation from the target. The range of Compton scattering angles,

TABLE III. Summary of (p,γ) and $(p,x\gamma)$ angular-distribution results for decay of 7.358-MeV level.

Distribution and energy of γ ray	Observed coefficients corrected for angular extent of detector $a_2\pm\Delta a_2$	$a_4\pm\Delta a_4$
(p,γ) 7.36 MeV	0.243±0.06	0.096±0.07
(p,γ) 6.14 MeV	0.012±0.025	−0.012±0.030
$(p,x\gamma)$ 1.22 MeV	−0.013±0.040	0.062±0.060

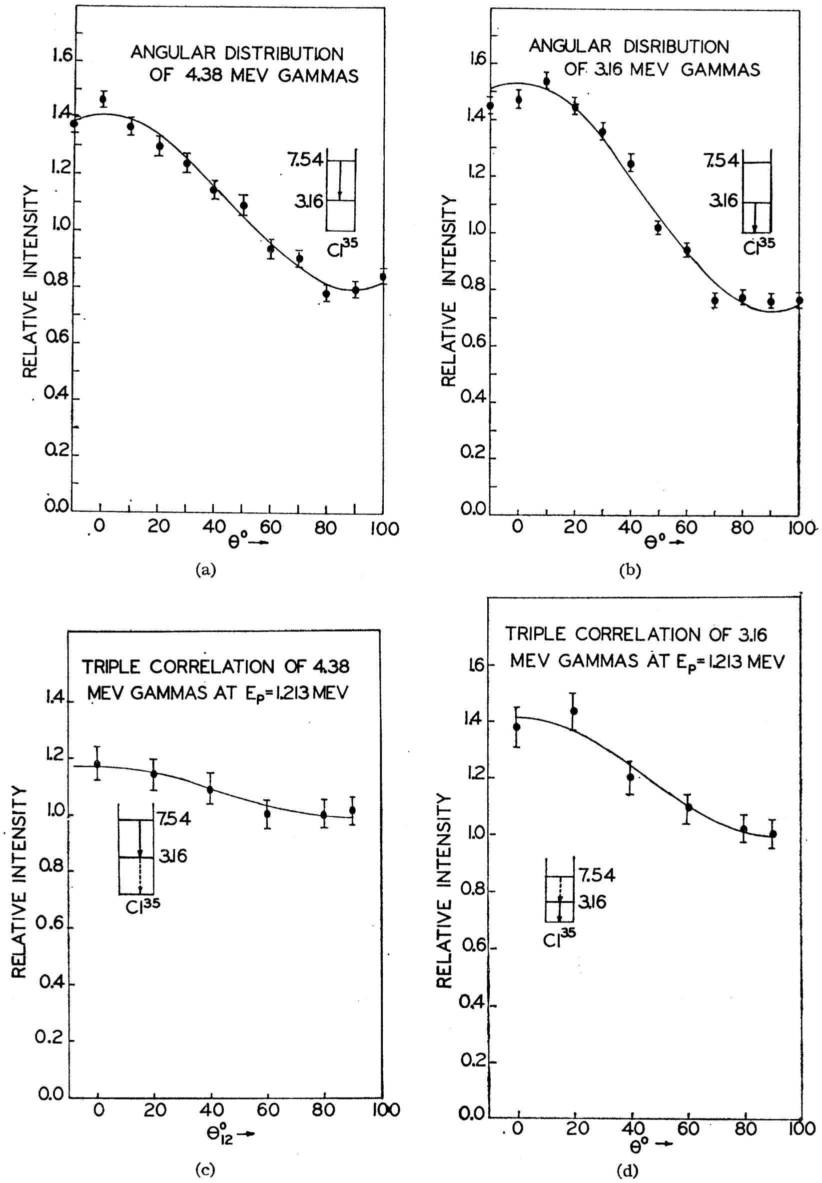

FIG. 7. Angular distributions and correlations for the decay of the 7.54-MeV level measured at a proton energy of 1.213 MeV. (a) and (b) show the measured angular distribution of the primary and secondary γ rays, respectively. (c) and (d) show the experimentally observed triple correlations for the γ-ray cascade from the 7.54-MeV level via the 3.16-MeV level, for "geometries" 1 and 2, respectively. The solid curves are least-squares fits to the experimental data.

θ, which were detected, was $60°\pm20°$. A schematic drawing of the polarimeter is shown in Fig. 4. Counts were taken for crystal No. 2 placed in four different positions for which $\phi=0°$, 90°, 180°, and 270° (see Fig. 4) thus reducing misalignment errors to second-order effects. The gains of the two detectors were equalized and their output pulses were added electronically. In addition, a linear gate was set on the spectrum of each crystal separately, wide enough to include, in the center crystal, the pulses from Compton recoil electrons corresponding to both γ rays of the cascade and all acceptable scattering angles and, in the movable crystal, wide enough to accept the corresponding full-energy pulses of the scattered γ rays. The resulting sum spectrum revealed a full-energy peak for each γ ray together with a low background outside the peak regions. The full-energy peaks were used in the analysis.

III. EXPERIMENTAL RESULTS AND ANALYSIS

In this section are given, separately, the experimental results for each of the three resonances.

A. Decay of the 7.358-MeV Level ($E_p=1.020$ MeV)

The relative intensities of the γ rays leading to the ground and first two excited states of Cl^{35} were deduced from the γ-ray spectra obtained in this experiment. As shown in Table II, these results are in agreement with those obtained by Hazewindus.[4]

TABLE IV. Values of p and q occurring in the summation of equation (2).

p	L_{12}	L_{12}	q	L_2	L_2
0	$\|J_1-J_2\|$	$\|J_1-J_2\|$	0	$\|J_2-I\|$	$\|J_2-I\|$
1	$\|J_1-J_2\|$	$\|J_1-J_2\|+1$	1	$\|J_2-I\|$	$\|J_2-I\|+1$
2	$\|J_1-J_2\|+1$	$\|J_1-J_2\|+1$	2	$\|J_2-I\|+1$	$\|J_2-I\|+1$

The angular distributions of the 7.36-, 6.14-, and 1.22-MeV γ rays were measured. A sum of even-order Legendre polynomials was fitted to each distribution by a least-squares method due to Rose.[12] The coefficients of the Legendre polynomials were normalized to $a_0=1.0$, for each distribution, and the errors shown for the normalized a_2 and a_4 coefficients include the experimental error in a_0. The experimental intensities and the fitted curve for the 7.36-MeV γ rays are shown in Fig. 5. The fitted coefficients were corrected for the finite angular extent of the counters using the attenuation factors tabulated byRutledge[13] and Gove and Rutledge[14] The results are summarized in Table III.

From the results on the 7.36-MeV γ-ray distribution a spin of $\frac{7}{2}$ for the resonance level is definitely ruled out since, for such a spin and the value of a_2 found in this experiment, a value of a_4 of the order of -0.8 would be expected. The observed value of a_4, slightly more than one standard deviation different from zero, may be due to statistical fluctuations. Thus the results are consistent with a spin of $\frac{5}{2}$ or $\frac{3}{2}$ for the resonance level since in the former case a_4 would have a value of 0.05 and in the latter case a_4 is rigorously zero. If the spin of the resonance level where to be $\frac{5}{2}$, the angular distribution of the 6.14 MeV γ-ray would then allow an assignment of spin $\frac{3}{2}$ for the 1.22-MeV level but would be inconsistent with a spin of $\frac{1}{2}$, as can be seen by a comparison of the coefficients of Table III with the graphs of Fig. 6. However, Davison and Wiesehahn[15] have studied the reaction $S^{34}(d,n)Cl^{35}$ and found an $l=0$ stripping pattern for the 1.22-MeV level whose spin and parity must be therefore $\frac{1}{2}^+$ .Thus, to be consistent with all the data available, including the angular distribution of the 6.14 MeV γ rays, the spin of the resonance level must be $\frac{3}{2}$.

B. Decay of the 7.544-MeV Level ($E_p=1.213$ MeV)

This level decays primarily through a state at 3.16-MeV which, in turn, decays 94% to the ground state and 6% to the 2.645-MeV level.[8]

Angular distributions, $(p,\gamma_{12}\gamma_2)$ triple correlations, and linear polarizations were measured to determine the spin and parity of the resonance and 3.16-MeV levels.

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

[13] A. R. Rutledge, Atomic Energy of Canada Report No. AECL-1450, 1959 (unpublished).

[14] H. E. Gove and A. R. Rutledge, Atomic Energy of Canada Report No. CRP-755, 1958 (unpublished).

[15] N. H. Davison and W. Wiesehahn (private communication).

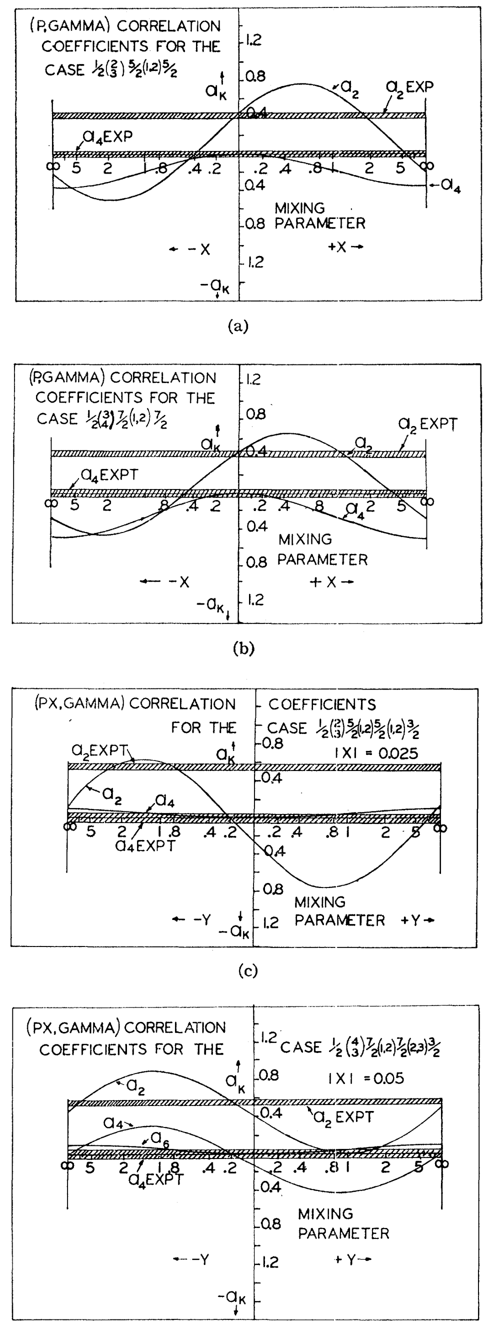

FIG. 8. Comparison of the measured angular-distribution coefficients with the predicted values for the 4.38–3.16-MeV ground-state cascade in the decay of the 7.54-MeV level. (a) and (b) show the theoretical (p,γ) angular-distribution coefficients as a function of the mixing parameter x for the spin sequences $\frac{5}{2}\rightarrow\frac{5}{2}$ and $\frac{7}{2}\rightarrow\frac{7}{2}$, respectively. The measured coefficients were obtained from the distribution of the 4.38-MeV γ rays. (c) and (d) show the theoretical (px,γ) angular distribution coefficients as a function of the mixing parameter y of the observed γ ray, for the spin sequences $\frac{5}{2}\rightarrow\frac{5}{2}\rightarrow\frac{3}{2}$ and $\frac{7}{2}\rightarrow\frac{7}{2}\rightarrow\frac{3}{2}$, respectively. The mixing parameter of the unobserved γ ray is taken to be $x=0.025$ for the first case and $x=0.05$ for the second case. The experimentally observed coefficients for the 3.16-MeV γ rays distribution are also shown.

TABLE V. Summary of angular-distribution and triple-correlation results for the decay of the 7.544-MeV level.

Correlation and energy of γ ray detected in movable crystal			Observed coefficients[a]		Best-fit coefficients and associated mixing ratios					
					$\frac{7}{2}\to\frac{7}{2}\to\frac{3}{2}$			$\frac{5}{2}\to\frac{5}{2}\to\frac{3}{2}$		
Type of correlation	Energy of γ ray (MeV)	Geometry	$a_2\pm\Delta a_2$	$a_4\pm\Delta a_4$	a_2	a_4	x,y	a_2	a_4	x,y
(p,γ)	4.38		0.42 ± 0.03	0.00 ± 0.03	0.42	0.00	$x=-0.05\pm0.05$	0.42	0.00	$x=-0.025\pm0.3$
(p,xy)	3.16		0.55 ± 0.03	0.01 ± 0.04	0.55	-0.02	$y=-0.16\pm0.05$	0.55	0.03	$y=0.80\pm0.10$
$(p,\gamma_{12}\gamma_2)$	4.38	1	0.112 ± 0.014	0.019 ± 0.019			$x=0.04\pm0.04$	No satisfactory fit.		
$(p,\gamma_{12}\gamma_2)$	3.16	2	0.248 ± 0.028	0.017 ± 0.047			and $y=-0.25\pm0.05$			

[a] The angular-distribution coefficients have been corrected for the finite extent of the detector.

The results of the (p,γ), $(p,x\gamma)$, and $(p,\gamma_{12}\gamma_2)$ measurements are given in Fig. 7. The curves were fitted by the procedures described above. The resulting angular distribution coefficients for the 4.38- and 3.16-MeV γ rays were compared to curves like those of Fig. 6 for all possible spin sequences up to $\frac{9}{2}$ and were found to be consistent only with $\frac{7}{2}\to\frac{7}{2}\to\frac{3}{2}$ and $\frac{5}{2}\to\frac{5}{2}\to\frac{3}{2}$ for the resonance level, 3.16-MeV level, and ground state, respectively. In Fig. 8 are shown the (p,γ) and $(p,x\gamma)$ curves, consistent with the experimental results and the deduced values of the mixing ratios, x and y, for the primary and secondary γ rays, respectively. The triple correlation method used in this work has been discussed by Ferguson and Rutledge,[11] who show that, for the geometries used in this experiment, the correlations will have the form

$$W(\theta)=\sum_k a_k P_k(\cos\theta), \quad (1)$$

where

$$a_k=\sum x^p y^q (-)^e \alpha_{kKM}{}^N Q_K Q_M \times D_{KM}{}^N(SIJ_1J_2l_1l_1'L_{12}L_{12}'L_2L_2'). \quad (2)$$

The summation is over allowed values of $KMNL_{12}L_{12}'L_2L_2'$. The value of e is given by $e=L_{12}+L_{12}'+L_2+L_2'$. The notation used here is illustrated in Fig. 9. The possible multipolarities of the γ ray transitions are limited by conservation of angular momentum, e.g., $|J_1-J_2|\leq L_{12},L_{12}'\leq|J_1+J_2|$, but in this analysis we have only considered the lowest two possible values of L for each transition.

The values of p and q depend on L_{12}, L_{12}' and L_2, L_2' as shown in Table IV. Q_K and Q_M are the correlation attenuation coefficients[13,14] which account for the finite angle subtended by the counters at the target. Definitions of and tables of values for the coefficients $\alpha_{kKM}{}^N$ and $D_{KM}{}^N$ are given in Ref. 11.

For a given set of quantum numbers, and for a given experimental arrangement, which determines the values of Q_K and Q_M, and $\alpha_{kKM}{}^N$, the coefficients a_k are functions of the two continuous variables x and y. Using the University of Toronto IBM 7094 computer, values of a_k were computed from Eq. (2) for sufficient points in the xy plane to allow plots to be made of the contours of the function $a_k(x,y)$. Such plots were constructed for many spin sequences $S\to J_1\to J_2\to I$ (see Fig. 9) and for the two geometries used in this experiment.[16] The contour plots were calculated using the attenuation coefficients $Q_2=0.945$, $Q_4=0.83$, and $Q_6=0.67$. These coefficients are appropriate to crystals No. 3 and No. 4 situated with their front faces 20 cm from the target and for γ rays of energies from about 1 to about 10 MeV. The spin sequences for which contour plots have been calculated are shown in Tables I, II, and III of Ref. 16.

Fits were made of Eq. (1) to the observed γ-ray intensities in the triple correlation measurements, by the same method as was used for the angular distributions.[12] The values of a_k thus obtained, together with their errors, were used to determine allowed regions of the xy plane. The spin sequences consistent with the experimental data are those for which at least one region of the xy plane was common for all coefficients a_k. The partial contour plots, showing the regions allowed by

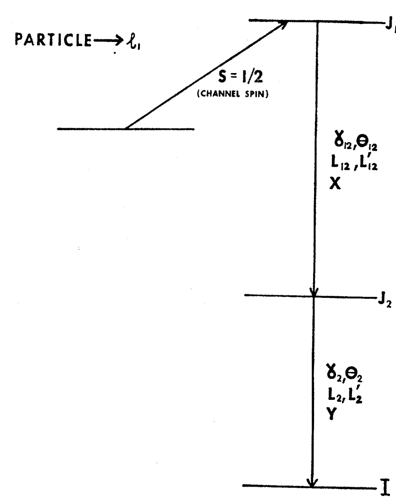

FIG. 9. The notation used for the description of the triple angular correlation of a γ-ray cascade initiated by a proton-capture process with channel spin $\frac{1}{2}$. θ_{12} is the angle at which γ ray γ_{12} is detected with respect to the beam direction. L_{12}, L_{12}' are the lowest two possible multipolarities of that γ ray while x is its multipole mixing ratio. θ_2, L_2, L_2', and y have the same significance for γ ray γ_2. l_1 is the orbital angular momentum of the bombarding particle.

[16] P. Taras and R. E. Azuma, Nucl. Instr. Methods 47, 116 (1967).

TABLE VI. Polarization results for decay of the 3.16-MeV level. Predicted values are for a spin sequence $\frac{7}{2}\rightarrow\frac{7}{2}\rightarrow\frac{3}{2}$ with the angular-correlation coefficients given in Table V.

N_0/N_{90}	Calculated R for polarimeter	Observed polarization P	Assumed radiation	Predicted polarization
1.29±0.13	1.41±0.04	0.00 to 0.384	$E3/M2$	0.106 to 0.077
			$M3/E2$	9.4 to 13

each measured coefficient, in the two triple correlations for the 4.38- and 3.16-MeV γ-ray cascade are shown in Fig. 10. It can be seen that there are two regions of overlap of all four bands for the sequence $\frac{7}{2}\rightarrow\frac{7}{2}\rightarrow\frac{3}{2}$, one of which agrees with the angular-distribution results. There is no such common region for the $\frac{5}{2}\rightarrow\frac{5}{2}\rightarrow\frac{3}{2}$ sequence. The results of the angular-distribution and correlation measurements are summarized in Table V.

The 3.16-MeV γ ray is thus a mixed quadrupole-octupole transition, connecting states of spin $\frac{7}{2}$ and $\frac{3}{2}$. The appreciable value of the mixing ratio suggests that the radiation is an $M2$-$E3$ mixture since it would be very unlikely to find $M3$ radiation competing with $E2$. The risk of such intensity arguments, however, is emphasized by the observation that, if the radiation is indeed $M2$-$E3$ then the 3.16-MeV level is $\frac{7}{2}^-$ and a possible $E1$ transition to the $\frac{5}{2}^+$ level at 1.76 MeV is not observed and must be extremely inhibited. (This branch of the decay of the 3.16-MeV level has been shown to contain less than 1% of the decay intensity.[8] The linear polarization of the 3.16- and 4.38-MeV γ-rays were therefore measured to determine the parities of the resonance and intermediate levels. The polarization results have already been reported[17]; the details are presented in this paper.

The Compton polarimeter used for these measurements was described in Sec. II. The principle of this type of polarimeter has been described by several authors and both the references to these papers and a discussion of the polarimeter may be found in the review article of Fagg and Hanna.[18] The Compton scattering cross section depends on the polarization of the incoming photons. Since the polarization of the scattered photons is unobserved, the cross section is given by[18]

$$d\sigma_\varphi=\tfrac{1}{2}r_0^2\frac{E^2}{E_0^2}\left(\frac{E_0}{E}+\frac{E}{E_0}-2\sin^2\theta\cos^2\varphi\right)d\Omega, \qquad (3)$$

where r_0 is the classical radius of the electron, $d\Omega$ is the element of solid angle into which the incident photon is scattered, θ is the angle of Compton scattering, φ is the angle between the polarization vector of the incident γ ray and the scattering plane, and E_0 and E are the energies of the incident and scattered photons, respectively. The ratio $R=d\sigma_{90}/d\sigma_0$ is then a measure of the polarization sensitivity for a point scatterer and

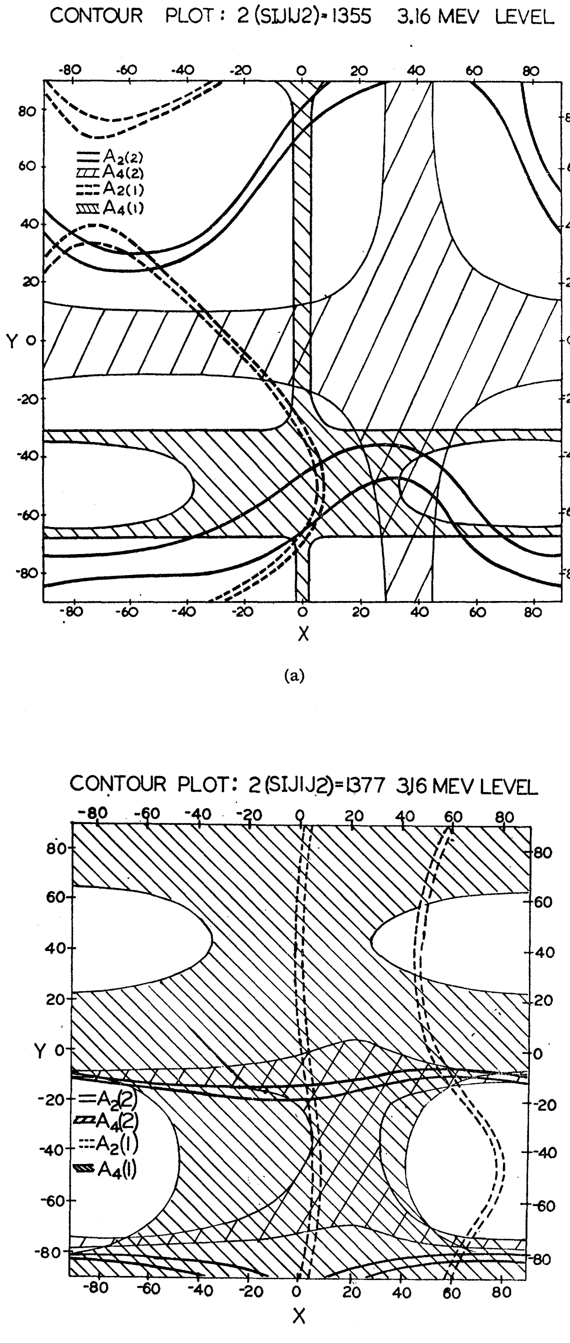

FIG. 10. Contour plots showing the allowed regions of the xy-plane defined by each of the measured triple correlation coefficients for the 4.38–3.16-MeV-ground-state cascade in the decay of the 7.54-MeV level. (a) $2(SIJ1J2)=1355$ represents the $\frac{5}{2}\rightarrow\frac{5}{2}\rightarrow\frac{3}{2}$ spin sequence with entrance channel spin $S=\frac{1}{2}$ as shown in Fig. 9. (b) Similarly $2(SIJ1J2)=1377$ represents the $\frac{7}{2}\rightarrow\frac{7}{2}\rightarrow\frac{3}{2}$ spin sequence. x and y are the amplitude mixing ratios for the primary and secondary radiations, respectively. $A_2(1)$ and $A_4(1)$ are the coefficients of P_2 and P_4, respectively, for geometry 1 while $A_2(2)$ and $A_4(2)$ apply to geometry 2. The scales are given in the form of arctan x and arctan y. The plot for the correct spin sequence (b) shows two regions where all coefficients allow the same x-y values.

[17] R. E. Azuma, L. W. Oleksiuk, J. D. Prentice, and P. Taras, Phys. Rev. Letters 17, 659 (1966).
[18] L. W. Fagg and S. S. Hanna, Rev. Mod. Phys. 31, 711 (1959).

TABLE VII. γ-ray intensities from the 7.841-MeV level.

Transition from resonance level to	Singles spectra (%)	Sum coincidence (%)
Ground state	17	(16)
1.22 MeV	35	34
2.645 MeV	...	2
3.006 MeV	...	7
4.17 MeV	48	41

detector, and has a value $R>1.0$. For a given γ-ray energy, θ may be chosen to maximize R but for a practical polarimeter a range of θ and φ is covered. For the polarimeter used in this experiment, R was calculated by dividing both the scattering and detecting crystal into elements and carrying out a numerical integration. The values thus obtained are given in Table VI.

The polarization measurements at angles $\varphi=0°$, 90°, 180°, and 270° were combined into ratios N_0/N_{90} for each γ ray and the polarization p was calculated from[18]

$$N_0/N_{90}=(p+R)/(pR+1), \tag{4}$$

where $p=J_0/J_{90}$ is the ratio of the intensity of γ rays polarized in the reaction plane to the intensity of γ rays polarized at right angles to the reaction plane.

The observed value of N_0/N_{90} found for the 4.38-MeV γ ray was 1.138 ± 0.11. Since the mixing ratio deduced from a weighted average of the angular distribution and triple correlation data is $x=0$, this result can be interpreted in terms of the simple formulae for pure dipole radiation given by McCallum[19] for the polarimeter at 90° to the proton beam direction:

$$\begin{aligned}&\text{magnetic dipole:}\quad p=(1+a_2)/(1-2a_2)\\&\text{electric dipole:}\quad p=(1-2a_2)/(1+a_2).\end{aligned} \tag{5}$$

With the measured value of $a_2=0.42\pm0.03$ from Table V and the observed value of the ratio N_0/N_{90} this would lead to an assignment of $E1$ for this radiation. However, subsequent results of Hazewindus[6] and Watson[7] conflict with this measurement although they confirm the present result for the 3.16-MeV γ ray. Their value of the ratio N_0/N_{90} is consistent only with an assignment of $M1$ for the 4.38-MeV γ ray.

The measurements of these polarizations have therefore been repeated in this laboratory by Wiesehahn.[8] The results obtained confirm those of Hazewindus and Watson for the upper γ ray and are in agreement with all three previous measurements for the 3.16-MeV level. We do not have any explanation for the discrepancy between our results and subsequent work except perhaps for statistical fluctuations, our value of N_0/N_{90} being different from the value obtained by Watson[7] by only three standard deviations.

The polarization results for the 3.16-MeV level are given in Table VI. For this γ ray of the cascade and $x=0$, the predicted polarization in the case of the $M2/E3$ mixture can be calculated using Eq. (6), derived by following the method outlined by McCallum[19]. Thus $p=N/D$, where

$$\begin{aligned}N=1&+\left[\frac{-2Z_1(2J2J,I2)-2.5\delta Z_1(2J3J,I2)+0.5\delta^2Z_1(3J3J,I2)}{Z_1(2J2J,I2)+2\delta Z_1(2J3J,I2)+\delta^2Z_1(3J3J,I2)}\right]\frac{a_2}{a_0}\\&+\left[\frac{-0.25Z_1(2J2J,I4)+\delta Z_1(2J3J,I4)-2.125\delta^2Z_1(3J3J,I4)}{Z_1(2J2J,I4)+2\delta Z_1(2J3J,I4)+\delta^2Z_1(3J3J,I4)}\right]\frac{a_4}{a_0}-0.75\frac{a_6}{a_0}\end{aligned}$$

and

$$\begin{aligned}D=1&+\left[\frac{Z_1(2J2J,I2)+0.5\delta Z_1(2J3J,I2)-1.5\delta^2Z_1(3J3J,I2)}{Z_1(2J2J,I2)+2\delta Z_1(2J3J,I2)+\delta^2Z_1(3J3J,I2)}\right]\frac{a_2}{a_0}\\&+\left[\frac{Z_1(2J2J,I4)+0.5\delta Z_1(2J3J,I4)+2.875\delta^2Z_1(3J3J,I4)}{Z_1(2J2J,I4)+2\delta Z_1(2J3J,I4)+\delta^2Z_1(3J3J,I4)}\right]\frac{a_4}{a_0}+0.125\frac{a_6}{a_0}\end{aligned} \tag{6}$$

In the case of the $E2/M3$ multipole mixture, $p=D/N$. The value of $y=-0.21\pm0.05$ derived from the two measured values in Table V yields, when substituted in Eq. (6), the predicted polarization values of Table VI, for the 3.16-MeV γ rays. Further details of the polarization experiment are given in Ref. 20.

The spin and parity of the 7.544-MeV level and of the 3.16-MeV level are thus found to be $\frac{7}{2}^-$, since the 3.16-MeV radiation is an $E3/M2$ mixture whereas the 4.38-MeV γ ray is pure $M1$ and the angular-correlation measurements allow only a spin of $\frac{7}{2}$ for these two levels.

[19] G. J. McCallum, Phys. Rev. **123**, 56 (1961).

[20] L. W. Oleksiuk, thesis, University of Toronto, 1962 (unpublished).

C. Decay of the 7.841-MeV Level ($E_p=1.513$ MeV)

The decay of this resonance level proceeds via a direct transition to the ground state and by four separate cascades through intermediate levels to the ground state. The branching ratios for the decay of the re-

TABLE VIII. Summary of angular-correlation results for the decay of the 7.841-MeV level.

Transition between levels (MeV)	Correlation and energy of γ ray detected in movable crystal: Type of correlation	Energy of γ ray (MeV)	Observed coefficients[a] $a_2 \pm \Delta a_2$	$a_4 \pm \Delta a_4$	Level considered (MeV)	Assumed spin	Mixing ratios x		y
$7.841 \to 0$	(p,γ)	7.841	0.41 ± 0.03	0.012 ± 0.04	7.841	$\frac{3}{2}$	Pure dipole		...
$7.841 \to 1.22$	(p,γ)	6.61	-0.46 ± 0.043	0.043 ± 0.057	1.22	$\frac{1}{2}$	$0.01 \leq x \leq 0.03$ or $-1.87 \leq x \leq -1.77$		All
$1.22 \to 0$	$(p,x\gamma)$	1.22	-0.01 ± 0.018	0.005 ± 0.024					
$7.841 \to 1.22 \to 0$	$(p,\gamma_1 2\gamma_2)$	6.61	-0.389 ± 0.017	0.019 ± 0.028					
$7.841 \to 1.22 \to 0$	$(p,\gamma_1 2\gamma_2)$	1.22	0.005 ± 0.029						
$7.841 \to 4.17$	(p,γ)	3.67	0.173 ± 0.01	-0.005 ± 0.013	4.17	$\frac{1}{2}$	$0.34 \leq x \leq 0.37$ or $-6.1 \leq x \leq -5.3$		All
$4.17 \to 0$	$(p,x\gamma)$	4.17	-0.011 ± 0.03	-0.006 ± 0.04		$\frac{3}{2}$	$-0.16 \leq x \leq -0.12$	$\leftrightarrow$	$\pm\infty$ or $0.23 \leq y \leq 0.33$
$7.841 \to 4.17 \to 0$	$(p,\gamma_1 2\gamma_2)$	3.67	0.141 ± 0.019	-0.023 ± 0.032			or $8.14 \leq x \leq 11.43$	$\leftrightarrow$	$\pm\infty$ or $0.23 \leq y \leq 0.29$
$7.841 \to 4.17 \to 0$	$(p,\gamma_1 2\gamma_2)$	4.17	0.010 ± 0.021			$\frac{5}{2}$	$-2.48 \leq x \leq -1.96$	$\leftrightarrow$	$-0.19 \leq y \leq -0.14$
							or $-0.29 \leq x \leq -0.22$	$\leftrightarrow$	$-0.25 \leq y \leq -0.19$
$7.841 \to 3.006 \to 0$	$(p,\gamma_1 2\gamma_2)$	4.84	-0.152 ± 0.043	-0.064 ± 0.059	3.00	$\frac{5}{2}$	$-0.03 \leq x \leq 0$		$0.05 \leq y \leq 0.10$
$7.841 \to 3.006 \to 0$	$(p,\gamma_1 2\gamma_2)$	3.00	-0.400 ± 0.022	-0.018 ± 0.042					

[a] The angular-distribution coefficients have been corrected for the finite extent of the detector.

sonance level are shown in Table VII. The cascades through the 2.645- and 3.006-MeV levels were observed only in the sum coincidence experiments as shown in Fig. 11. The intensity of the cascade through the 2.645-MeV level was too weak to yield significant angular-correlation data.

The type of angular correlations and results for the γ rays associated with the decay of this resonance level are listed in Table VIII. These distributions and correlations were performed and analyzed in a manner similar to that described for the transitions examined at the $E_p = 1.020$-MeV and 1.213-MeV resonances.

The resulting angular-distribution coefficients for the 7.841-MeV γ rays were compared to curves like those of Fig. 6 for all possible spins up to $\frac{7}{2}$ and were found to be consistent only with a spin of $\frac{3}{2}$ for the resonance level. The measurements associated with the level at 1.22-MeV are consistent with its known spin of $\frac{1}{2}$,[15] while those associated with the 4.17-MeV level do not yield positive spin assignments. The restrictions on the spins of the 4.17-MeV level are shown in Table VIII, when a spin of $\frac{3}{2}$ is assumed for the resonance level.

The 7% cascade through the 3.006-MeV level has been observed in the sum coincidence spectrum. The triple correlations, for two geometries, were performed and the results are also shown in Table VIII. A spin

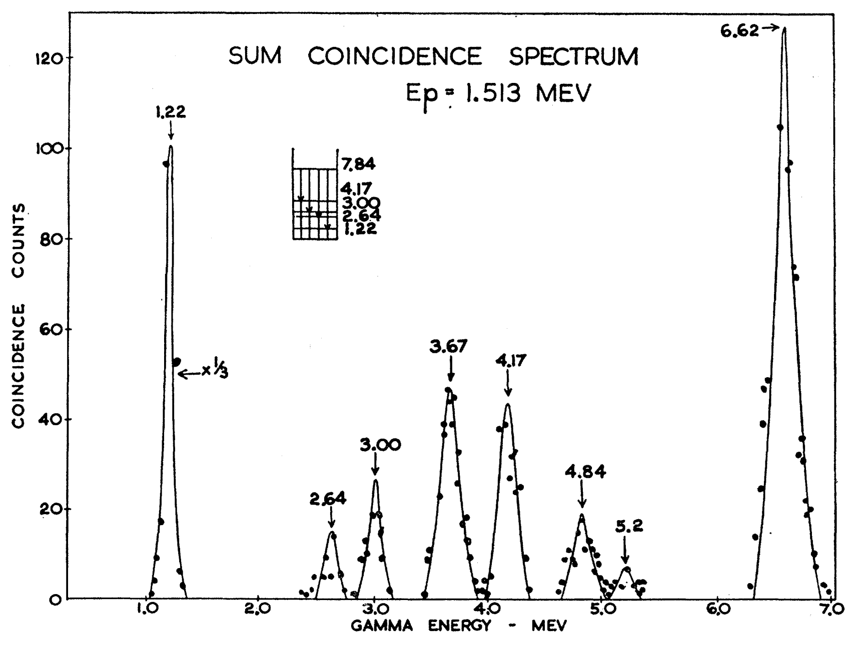

FIG. 11. The sum-coincidence spectrum for the γ rays in cascade from the 7.84-MeV level, populated at $E_p = 1.513$ MeV.

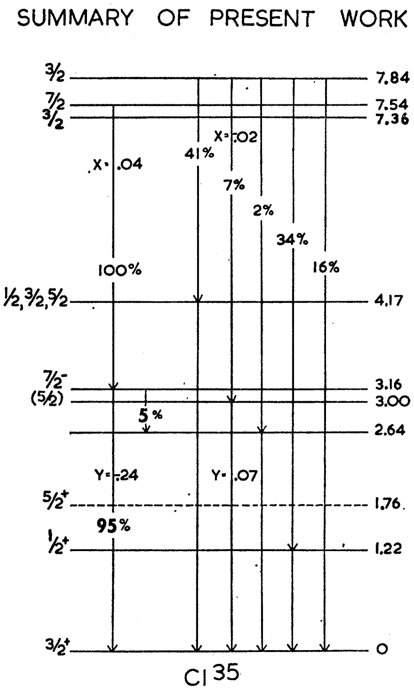

FIG. 12. Summary of the experimental information established in the experiments reported here. The energies are given in MeV. The spin of the 3.00-MeV level is considered to be tentative. The 1.76-MeV level has not been studied in this work but is included because it is relevant to the discussion.

assignment of $\frac{5}{2}$ is the only one consistent with the triple correlation coefficients. However, since the intensity of the γ ray to this level is only 7%, considerable systematic uncertainties could exist in the experimental results. For this reason, the assignment of spin $\frac{5}{2}$ to the 3.006-MeV level should be considered as tentative.

IV. DISCUSSIONS AND CONCLUSIONS

The results of the present measurements are summarized in Fig. 12. The spin and parity of the 3.163-MeV level has been found to be $\frac{7}{2}^-$ by triple correlation and polarization experiments. This level decays by an $E3/M2$ admixture to the ground state, with a mixing ratio of $y=-0.25\pm0.05$. The mean lifetime of this level has been measured by Azuma *et al.*[21] by the delayed coincidences method and was found to be $\tau_\gamma(3.163\text{ MeV})=(1.36\pm0.39)\times10^{-10}$ sec. From this value of the lifetime and the value of the mixing ratio found in this experiment, the reduced transition probabilities can be calculated. They are $|M(M2)|^2=7.5\times10^{-2}$ Weisskopf units (W.u.) and $|M(E3)|^2=2.7$ W.u. Such values are reasonable for these multipolarities.

It is of interest to note that a possible transition from the 3.163- to the 1.762-MeV level has been shown to be less than 1% of the intensity to the ground state.[6,8] The 1.762-MeV level has been assigned a spin of $\frac{5}{2}$ by Storey and Oleksiuk[22] on the basis of a small $P_4(\cos\theta)$ component in the angular distribution of the 1.76-MeV γ ray produced by inelastic proton scattering on Cl.[35] Similar measurements by Erné[23] confirm the finite $P_4(\cos\theta)$ component, thus adding weight to the $\frac{5}{2}$ assignment. If, indeed, this assignment is correct, then all the above results imply an extremely inhibited $E1$ transition between the 3.163- and the 1.762-MeV level. On the basis of the delayed coincidence lifetime, the inhibition is 10^{-8} of a single-particle unit. This inhibition is much greater than would normally be expected. No satisfactory theoretical explanation has yet been presented to account for this exceptionally large inhibition.[24] Of the above results, the least firmly established are the spin and parity of $\frac{5}{2}^+$ for the 1.762-MeV level.

The energies, spins, and parities of the levels in Cl^{35} up to 6 MeV have been interpreted on the basis of the unified model. The predictions are consistent with the present experimental data; only the level at 3.00 MeV is not accounted for. Further details are given by Taras.[24]

---

[21] R. E. Azuma, A. M. Charlesworth, and N. Anyas-Weiss (to be published).
[22] R. Storey and L. W. Oleksiuk, Can. J. Phys. 39, 917 (1961).
[23] F. C. Erné, Nucl. Phys. 84, 241 (1966).
[24] P. Taras, Can J. Phys. 44, 1563 (1966).