Low-Lying Levels of ^{35}Cl and ^{37}Cl†

D. D. DUNCAN,* K. H. BUERGER, R. L. PLACE, AND B. D. KERN
Department of Physics and Astronomy, University of Kentucky, Lexington, Kentucky 40506
(Received 7 April 1969)

γ-ray energies and branching ratios for the first six excited levels of ^{35}Cl and the first three levels of ^{37}Cl have been measured. Proton–γ-ray coincidence techniques were used to obtain p-p'-γ correlations by means of the ^{35}Cl$(p, p'\gamma)^{35}$Cl and ^{37}Cl$(p, p'\gamma)^{37}$Cl reactions, with the inelastically scattered protons being detected at approximately 180° with respect to the beam axis. Analysis of the p-p'-γ correlations placed limits on the spins and the electromagnetic multipole mixing ratios. The attenuated-Doppler-shift method was used to determine nuclear lifetimes for the first five excited levels of ^{35}Cl and the first two excited levels of ^{37}Cl. All available data have been summarized and used in calculating radiative widths and multipole strengths.

I. INTRODUCTION

DURING the past few years, the use of nuclear models has made possible the explanation of the structure of ^{35}Cl and ^{37}Cl with varying degrees of success. The present study of the decay properties of levels of these nuclei through the ^{35}Cl$(p, p'\gamma)$ and ^{37}Cl$(p, p'\gamma)$ reactions was initiated in order to add more data to those which were available for use in the testing of the models. In particular, the larger-scope shell-model calculations are yet to be tested in the upper portion of the $2s$-$1d$ shell. γ-ray branching ratios were measured. Triple angular correlations (p-p'-γ) were obtained according to method II of Litherland and Ferguson[1,2] with an annular p' detector which was centered on 180° with respect to the incident proton beam. Abundant details concerning this method have been given by others[3,4] and need not be repeated here. With the use of coincidence counting techniques, this study has resulted in corrections and additions to the γ-ray branching ratios, in the setting of limits on the possible spins and on the electromagnetic multipole amplitude mixing ratios, and in more precise values of the energies of several levels of ^{35}Cl and ^{37}Cl. Nuclear lifetimes have been measured by the attenuated-Doppler-shift method for the first five levels of ^{35}Cl and the first two levels of ^{37}Cl.

Previous Studies

Earlier experimental studies of various reactions have established the energies of ^{35}Cl and ^{37}Cl levels to energies above 7 MeV of excitation and the spin-parity of many of these levels (some of which are shown in Fig. 1). These studies include those of the (p, p') reaction,[5,6] the extensive work on ^{34}S$(p, \gamma)^{35}$Cl by Hazewindus *et al.*,[7] the $(p, p'\gamma)$ study[8] which gave spin assignments of $\frac{1}{2}$ and $\frac{5}{2}$ to the first two excited levels of ^{35}Cl, the β-decay study[9] of ^{35}Ar which gave even-parity assignments to those two levels just mentioned, and the β-decay study[10] of ^{37}S which gave odd-parity assignments to the 3105- and 3708-keV levels of ^{37}Cl. The ^{35,37}Cl$(n, n'\gamma)$ report[11] confirmed the ^{35}Cl assignments of $\frac{1}{2}$ and $\frac{5}{2}$ for the first two excited levels and added spin $\frac{7}{2}$ for the 2646-keV third excited level; it also confirmed the assignment of spin $\frac{1}{2}$ for the first excited level of ^{37}Cl and added $\frac{5}{2}$ for the 3708-keV fifth excited level. For the 3002-keV level of ^{35}Cl, only the energy was known.[7] There was disagreement between Refs. 7 and 11 as to the branching ratios for γ-ray emission from the 2646- and 2695-keV levels of ^{35}Cl. This earlier work has been reviewed in Refs. 10 and 11. Erné[12] has confirmed the spin-parity of the 1763-keV level as $\frac{5}{2}^+$ through angular distribution and polarization measurements with the ^{35}Cl$(p, p'\gamma)$ reaction, and has given a value for the multipole mixing ratio for the transition from this level to the ground level.

More recently, it has been established that the 3163-keV level[13–16] of ^{35}Cl and the 3105-keV level[17] of

† Supported in part by the National Science Foundation.
* Present address: Murray State University, Murray, Ky.
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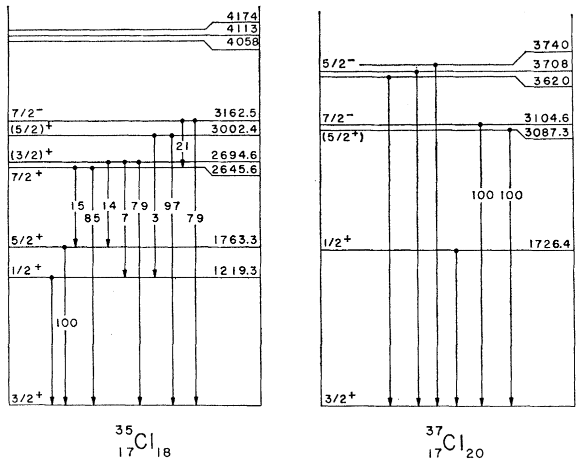

FIG. 1. Low-lying levels of ^{35}Cl and ^{37}Cl. The energies and the branching ratios for the first six excited levels of ^{35}Cl, and the energies of the first three excited levels of ^{37}Cl, are results of this study.

^{37}Cl are $T_<$ levels with spin-parity $\frac{7}{2}^-$, through γ-γ angular correlations taken with the $(p, \gamma\gamma)$ reactions. Azuma *et al.*[18] have measured the mean life of the 3163-keV level as $\tau = 1.4\times10^{-10}$ sec and Wiesehahn and Prentice[19] have reported recently a value of the branching ratio. A detailed and exhaustive study[20] of the ^{36}S$(p, \gamma\gamma)^{37}$Cl reaction provides information about several additional levels of ^{37}Cl and their parameters.

Reasonable success has been achieved in describing the structure of these nuclei with an asymmetrical-core collective model,[21] a shell model with inert core and two-particle interactions,[22] a similar shell model with $f_{7/2}$ states included,[23] unified models,[24,25] and a model with core polarization.[26]

II. EXPERIMENTAL DETAILS

Protons with energies from 4.591 to 6.195 MeV were collimated to a beam 0.160 cm in diameter and directed through thin targets of $CdCl_2$. Beam currents were typically 0.05 μA and were measured with a Faraday cup and a current integrator circuit. The targets were evaporated films on Au substrata; a typical target had surface density of approximately 100 μg/cm^2 of $CdCl_2$ enriched[27] to 99.00% in ^{35}Cl or to 99.28% in ^{37}Cl, on approximately 200 μg/cm^2 of Au. The targets were mounted on the axis of a cylindrical aluminum-walled vacuum chamber of 6.35-cm outside radius.

Elastically and inelastically scattered protons were detected by a 300-μ-depth annular surface-barrier detector which was located with its axis of symmetry on the beam axis. It was 4 cm from the target and received protons which were scattered at angles between 172.0° and 174.5° relative to the direction of the beam. A movable 390-μ-depth surface-barrier detector was located at a radial distance of 2.0 cm from the target; it could be rotated to angles from 20° to 148° relative to the direction of the beam and was used as a monitor and also for obtaining 90° differential cross sections. The resolution of these detectors was 24 keV, full width at half-maximum.

γ rays were detected with a 7.62×7.62-cm-diam NaI(Tl) crystal, located with the crystal face at 10 cm from the target, and movable in the reaction plane from 0° to 135° relative to the beam axis. At times, two such crystals were used simultaneously. In other phases of the study, 15- and 35-cc Ge(Li) crystals were utilized.

Standard high-resolution electronic circuitry was used. A fast-slow coincidence system was operated with resolving times 2τ of 50–100 nsec. Accidental coincidences accounted for 5–15% of the total counts, with there being a much smaller percentage included in the γ-ray total energy peaks.

Single-channel analyzers were used to select p' pulses to act as gating pulses for the coincidence circuit, and the coincident γ-ray pulse-height spectra were accumulated by a 4096-channel analyzer, with selective storage of real-plus-accidental coincidence counts and of accidental coincidence counts.

In collecting p'-γ coincidence data, the p' groups of interest were accumulated separately in a 400-channel analyzer to provide normalization between data acquired at the several γ-ray detector angles. During the cross-section measurements, the proton beam current was integrated to provide the normalizing factor. The use of an extension tube between the target chamber and the Faraday cup (to decrease the background) limited the minimum angle to 31°; however, at some bombarding energies it was possible to use a cup inside the target chamber and to move the γ-ray detector to 0°.

III. ACQUISITION OF DATA

Excitation Functions

The first step was to measure the cross section for the production of each of the final levels of the (p, p') reaction. Although resonances were in no way necessary for the analysis, it did prove to be necessary to take data at p' resonant maxima due to the generally

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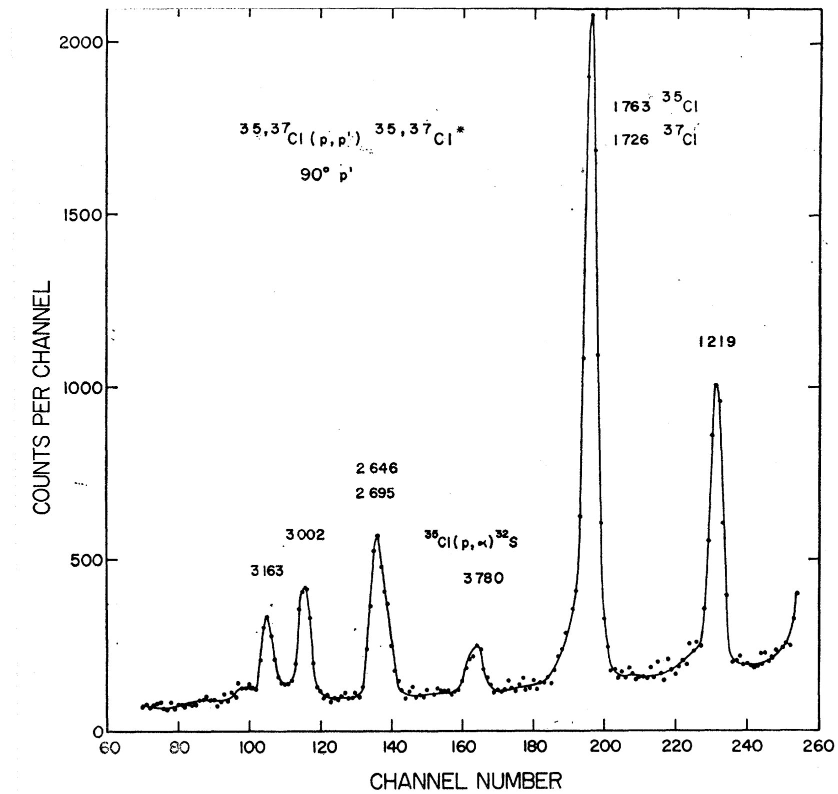


FIG. 2. Particle spectrum, observed at 90° to the beam axis with a surface-barrier detector, due to 5.24-MeV protons on a thin $CdCl_2$ target. Lines not otherwise marked are due to the $^{35}Cl(p,p')^{35}Cl$ reaction. The excited level energies are in keV.

low yield. The p' detector was positioned at 90° to the beam axis and was used to acquire spectra such as the typical one of Fig. 2. Many resonances were present in the cross sections, with maxima as high as 11 mb/sr but with more typical values of about 4 mb/sr. These 90° (p, p') differential cross sections are shown in Fig. 3. The targets were $CdCl_2$ of normal isotopic composition and hence the yield of the unresolved p' groups for the 1763-keV (^{35}Cl) and the 1726-keV (^{37}Cl) levels is due principally to ^{35}Cl. For the 3087- and 3105-keV levels of ^{37}Cl there was no resolvable yield.

At 180°, as detected with the annular counter, the yields of the resonances seen at 90° were typically very low and it was necessary to locate other maxima in the yield. No general survey was made; the energies at which these maxima for each level were found at 180° are cited in Sec. IV.

Proton-γ Coincidence Spectra

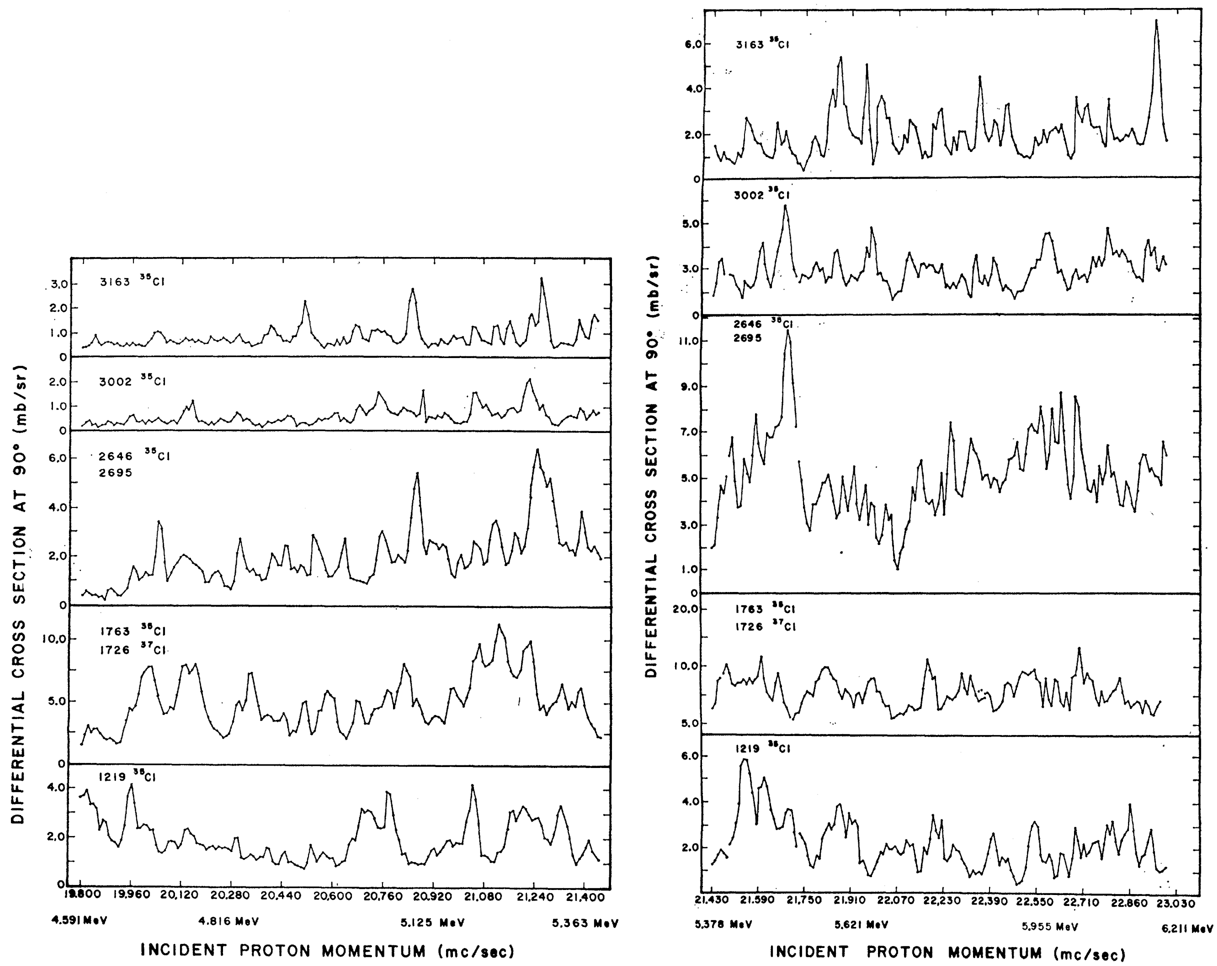
Pulses from the γ-ray detector were admitted to a multichannel analyzer if they were in coincidence with a p' group selected by use of a single-channel pulse-height analyzer. Spectra were accumulated at five to eight angles between 0° and 90°, requiring 1–4 h per angle. In most sequences the spectra were corrected for contributions from accidental p'-γ coincidences. Selected incident proton energies in the range 4.70–5.42 MeV were found to give a yield of p' groups which was adequate for the triple-angular-correlation studies. Typical coincidence spectra are shown in Fig. 4. Relative γ-ray intensities were determined by a computer "stripping" analysis of each spectrum, which was followed by correction for the relative detection efficiency.

Branching Ratios of ^{35}Cl Levels

The relative intensities of the γ rays emitted from those levels which decay by more than one transition were determined through analysis of the p'-γ coincidence correlation data. The coincident γ-ray spectra were decomposed by a computer stripping program and the γ-ray yields were compared after correction for the detector efficiency and for absorption by the walls of the chamber. The resulting branching ratios are given in Table I in percent of all transitions from each level. Because of the widely differing intensities and certain resolution problems, the treatment of each level was an individual one.

For the 1763-keV level, the p'-γ angular correlation spectra individually showed no indication of cascade radiation [Fig. 4(a)]. As a check, the p'-γ spectra were summed by channels to reduce the statistical uncertainties in the counts per channel and the resulting spectrum was decomposed, with the conclusion that only the ground level transition was present, to within 3%.

For the 3002-keV level, again, the p'-γ angular



(a) (b)

FIG. 3. Differential cross sections for the ^{35,37}Cl$(p, p')^{35,37}$Cl reaction. The p' detector was located at 90° to the beam axis. The thin $CdCl_2$ target contained the normal mixture of the two isotopes. Uncertainties in the target thickness determination causes a possible error of $\pm 50\%$ in the absolute value of these cross sections. (a) 4.591–5.378 MeV; (b) 5.378–6.195 MeV.

correlation spectra individually showed no indication of cascade radiation. In order to reduce the statistical uncertainty, a spectrum was acquired with two 7.62$\times$ 7.62-cm-diam NaI(Tl) crystals placed diametrically opposite at 90° to the beam axis. The annular particle detector was used. A p'-γ coincidence spectrum was accumulated over a period of 16 h. The spectrum of random coincidences was accumulated and later subtracted; 7% of the counts were due to random coincidences. Analysis of the spectrum gave a $(3\pm 1)\%$ branching to the 1219-keV level. No correction could be made for the probable but unknown anisotropy of the (3002→1219) radiation, but the large solid angle subtended at 90° by the γ-ray counters gave a good sample of the spherical distribution, and the branching ratio will not be appreciably in error unless the angular correlations of the two competing radiations are greatly different.

The determination of the branching from the 2646- and 2695-keV levels was complicated by the fact that the emitted γ rays could not be resolved with the NaI(Tl) crystal detectors. However, it was possible to resolve the two p' groups with the use of a high-resolution collimator to the extent that relative p' yields could be measured, but not well enough so that one p' group could be isolated for gating purposes. An analytical method was used to determine the relative γ-ray yields from each level. As before, two NaI(Tl) crystals were used, but the p' detector was located at 145°. The p' and the p'-γ coincidence spectra were obtained at two bombarding energies, which were selected as having a high yield for the one or the other of the two p' groups. At $E_p=4.72$ MeV, the p' spectrum was decomposed to yield a ratio of p' intensities $I(2646)/I(2695)=0.07\pm 0.01$; at $E_p=5.09$ MeV the ratio was 4.17 ± 0.11. In taking the p'-γ

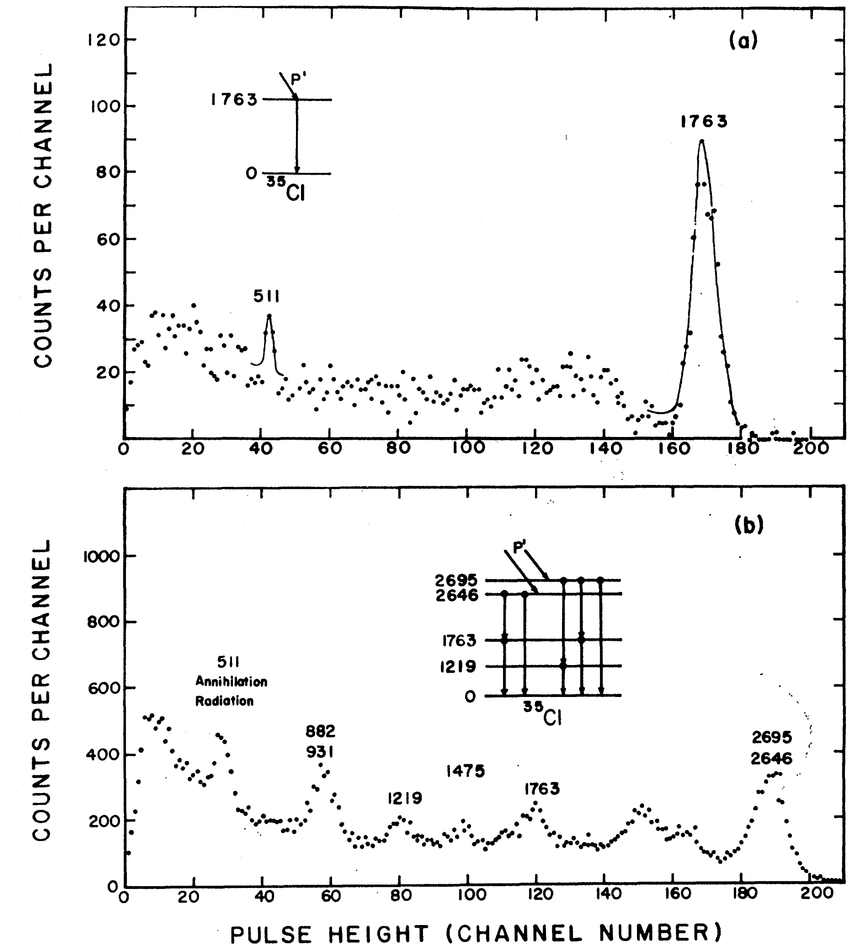


FIG. 4. Spectra of γ rays, observed with a NaI(Tl) crystal detector at 90° to the beam axis, in coincidence with inelastically scattered protons. (a) Protons leaving ^{35}Cl in the 1763-keV level were detected near 180° by an annular surface-barrier detector. (b) Two levels contributed to the inelastically scattered protons detected at 145°. The 2646-keV level was populated with intensity 4.17 times larger than the 2695-keV level.

TABLE I. Energies and branching ratios of the low-lying levels of ^{35}Cl and ^{37}Cl as determined by γ-ray measurements in the present work. The observed energies of cascade γ rays are also listed.

Level (keV)	Transition	Branching ratio (%)
^{35}Cl		
1219.3±0.3	→0	100 (first excited level)
1763.3±0.3	→0	100^{+0}_{-3}
2645.6±0.5	→0	85±3
	→1763.3	15±3
2694.6±0.5	→0	79±3
	→1219.3	7±3
	→1763.3	14±3
3002.4±1.0	→0	97±1
	→1219.3	3±1
3162.5±1.0	→0	79±5
	→2645.6	21±5
^{37}Cl		
1726.4±0.3	→0	100 (first excited level)
3087.3±1.0	→0	$100^{+0}_{-(\approx 5)}$
3104.6±1.0	→0	$100^{+0}_{-0.5}$[a]
^{35}Cl cascade γ rays		
517.0±0.8	3162.5→2645.6	
882.3±0.3	2645.6→1763.3	
931.3±0.3	2694.6→1763.3	
1475±2	2694.6→1219.3	

[a] From Ref. 10.

coincidence spectrum, a low-resolution collimator was used in order to increase the counting rate, and both p' groups triggered the coincidence circuit; thus in the γ-ray spectrum was a mixture of the radiations from the two levels, as illustrated in Fig. 4(b). Each of the two γ-ray spectra yielded two γ-ray intensity ratios, i.e., the ratios of the combined 2646- and 2695-keV γ-ray intensity to the 1763- and 1219-keV γ-ray intensities. Thus, the data consisted of two p' and four γ-ray intensity ratios; four simultaneous equations could be formulated from which it was possible to extract two relative intensities (branching ratios) per level, by solving the equations for an optimum solution with a least-squares method. The results are listed in Table I. These ratios have not been corrected for the probable but unknown anisotropies in the angular correlations. A (3±3)% transition from the 2646- to the 1219-keV level is given by this method but there is no other evidence for this transition.

In the case of the 3163-keV level, the individual method-II angular correlation spectra were decomposed to give the yields of the 3163-keV γ-ray relative to the 2646-keV cascade γ ray. The yields were in

TABLE II. Summary of the p'-γ correlation results. Each γ-ray transition was to the $\frac{3}{2}^+$ ground energy level.

Isotope	Level (keV)	Most probable J^π	Incident proton energy E_p (MeV)	p'-γ correlation coefficients of Legendre polynomial sum A_2/A_0	A_4/A_0	Best value of δ or limits on δ
^{35}Cl	1219.3	$\frac{1}{2}^+$	4.65	0.02±0.06	0.05±0.09	not dependent on δ
	1763.3	$\frac{5}{2}^+$	4.74	−0.02±0.02	0.07±0.02	$-\infty$ to −0.40; 0.40 to ∞
	2645.6[a]	$\frac{7}{2}^+$	4.74	0.22±0.05	−0.13±0.06	≈0
	3002.4	$\frac{5}{2}^+$	5.11, 5.43	−0.30±0.04	···	−20 to −0.30; 0.20 to 5
	3162.5	$\frac{7}{2}^-$	5.20	0.45±0.01	···	$\delta=-0.14_{-0.06}^{+0.08}$
			5.42	0.48±0.21	−0.13±0.73	
^{37}Cl	1726.3	$\frac{1}{2}^+$	4.70, 5.00	−0.08±0.08	−0.11±0.11	not dependent on δ

[a] Contained a contamination from the 2695-keV level.

the same ratio at all observed angles, so the individual spectra were added by channels to obtain a spectrum which was stripped to give the final result of (79±5)% to the ground energy level and (21±5)% to the 2646-keV level.

Ge(Li) Crystal-Detector Spectra

Protons of energy 5.6 MeV were used to bombard thick targets of ^{35}Cl and ^{37}Cl, which were formed by making a slurry of $CdCl_2$ and alcohol and allowing it to dry on a tantalum foil, with surface density of approximately 10 mg/cm^2. The beam was collimated as before and allowed to pass through the target chamber into an extension tube on the end of which was mounted a thick target, oriented at 45° to the beam. A 35-cc Ge(Li) crystal detector was placed at approximately 10 cm from the target at angular positions of 0°, 30.5°, 54.7°, or 90° relative to the beam axis. Each spectrum was accumulated during a period of 1 h in 4096 channels of a multichannel analyzer at a dispersion of 0.98 keV/channel. At each angular position, energy calibration was achieved by placing radioactive sources of ^{60}Co and ^{88}Y nearby, so that their γ-ray lines also appeared in each spectrum, with energies of 511.006, 814.12, 898.04, 1173.23, 1332.49, and 1836.13 keV. Internal calibration points of less precision were the 2126.8±0.8-keV line from the ^{37}Cl$(p, \alpha\gamma)^{34}$S reaction and the 3105±1-keV line from ^{37}Cl previously observed here in a study of the β decay of ^{37}S. Between some of these spectra, a ^{232}Th source was used to produce a spectrum with calibration points at 1592.46 and 2614.47 keV due to the high-energy γ ray emitted in the decay of ^{208}Tl. The proton beam was limited to a few nanoamperes in order to preserve good resolution; for the lines which were not Doppler-broadened the resolution was 4 keV, full width at half-maximum.

The 90° spectra were used in the determination of the γ-ray energies. The location of the centroid of each of the lines of known energy was calculated first for each spectrum. Unknown energies of two-escape peaks and/or total energy peaks were established by interpolation between calibration points. Higher-energy calibration points (above 2614.47 keV) were established by assigning to the higher-intensity total energy peaks of the 3002- and 3163-keV radiations their energies as determined through the observation of their two-escape peaks. The γ-γ cascade energy sums were also used to verify the energies of the higher-energy γ rays. The 517-keV γ ray emitted from the 3163-keV level was difficult to resolve from the intense 511-keV mc^2 line; however, through a direct comparison between the spectra from a ^{35,37}Cl target and a ^{37}Cl target, it was possible to subtract the 511-keV contribution. The results of the γ-ray energy measurements, which led to assignments of energies to the various levels, are listed in Table I.

During an earlier data-acquisition sequence, a 1024-channel multichannel analyzer was used, with a 15-cc Ge(Li) crystal detector and a biased amplifier, at dispersion of 1.9 keV/channel. A background spectrum was obtained for each range of energies covered by the analyzer by causing the beam to strike the reverse side of the target foil. The response of the detection system was corrected for minor nonlinearities through the use of a linear pulse generator. The γ-ray energies which were obtained were practically the same as those reported in Table I, but had attached to them somewhat larger uncertainties.

IV. RESULTS

The data and the results of analysis will be discussed separately for each energy level. The branching-ratio results are summarized in Table I. The energies of the levels as given in Table I are very close to those of earlier reports. There is no evidence for closely spaced levels which might have been unobserved previously.

Angular-Correlation Measurements

The coincident γ-ray yields versus angle are displayed in the figures and the coefficients obtained through a least-squares fitting to the data of $Y(\theta)=\sum_k A_k P_k(\cos\theta)$, with $k=0$, 2, and 4, are listed in Table II.

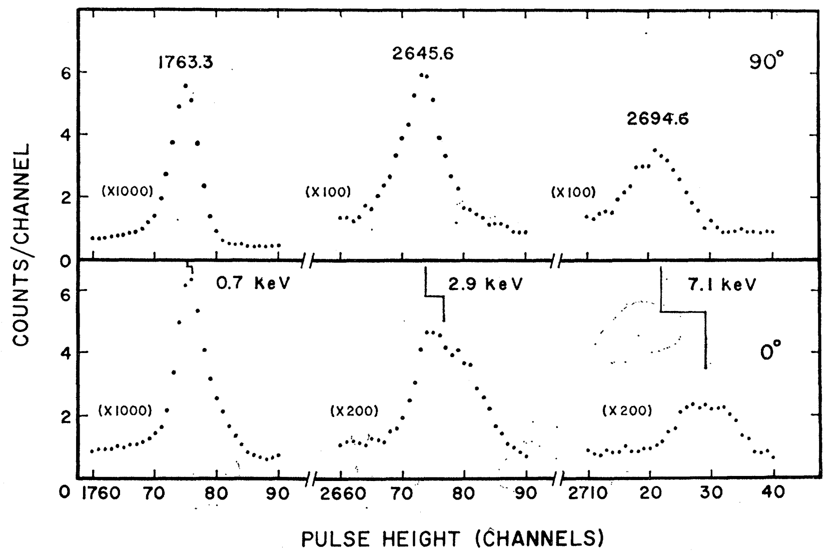


FIG. 5. Portions of 90° and 0° γ-ray spectra as obtained with a 35-cc Ge(Li) crystal detector. The γ rays were emitted following the ^{35}Cl(p, p') reaction. The average incident proton energy was 5.4 MeV.

It was not possible to make spin assignments on the basis of the angular correlations alone, but this was not unexpected, since magnetic substates of up to $\pm\frac{5}{2}$ could be populated and thus up to three adjustable population parameters were involved. Nevertheless, the analysis was carried out. Given a known value for the spin, it was possible to set limits on the possible values of the multipole amplitude mixing ratios, as summarized in Table II.

In the analysis of the correlation data, Ferguson's[2] equation (3.48) with $k=0$, 2, 4, and 6 was used. An initial selection was made of a trial value of J, the spin of the residual level, and of $\delta(L'/L)$, the electromagnetic multipole amplitude mixing ratio; with these the theoretical angular correlation for each possible magnetic substate was calculated. These theoretical correlations were then combined linearly with magnetic substate population parameters as weighting factors in such a way as to reproduce the data correlation $Y(\theta)$. A linear least-squares method was used to adjust the population parameters; the requirement that each parameter be a positive number was made and any negative parameter was set equal to zero and the fitting was repeated before the final calculation of the theoretical correlation $W(\theta)$ was made. To test the goodness of fit of the theoretical correlation $W(\theta)$ to the data correlation $Y(\theta)$, a normalized χ^2 function $Q^2=\chi^2/(N-n-1)$ was calculated.[28] Here, N is the number of angles at which γ-ray yields were obtained and $n\leq 3$ is the number of population parameters. Such a calculation was made for each trial value of J from $\frac{1}{2}$ to $\frac{7}{2}$ for 157 values of δ from -92 to $+92$; the results are displayed as graphs of $\chi^2/(N-n-1)$ versus $\arctan\delta$.

[28] A. H. Wapstra, G. J. Nijgh, and R. Van Lieshout, *Nuclear Spectroscopy Tables* (North-Holland Publishing Co., Amsterdam, 1959).

Mean Lifetimes by Attenuated-Doppler-Shift Method

Nuclear lifetimes have been determined from the Ge(Li) crystal-detector spectra. Most of the lines in the spectra show Doppler broadening when observed at 90° to the incident proton beam and Doppler shifts when observed at 0°. Portions of two typical spectra are shown in Fig. 5, with three of the lines due to ^{35}Cl, as observed at 90° and at 0°. In these spectra, the radioactive source lines, the 3163-keV line of ^{35}Cl and the 3105-keV line of ^{37}Cl, show no Doppler broadening and no Doppler shift. The Doppler shift, when observed, appears because the recoil Cl nuclei, produced by the (p, p') reaction with $E_p=5.6$ MeV, all travel within a cone of half-angle of 39.5° (3163-keV level) to 61.2° (1219-keV level), centered on the beam axis. The Doppler shift was attenuated because of the slowing down of the Cl ions in the thick target of $CdCl_2$, which was of surface density $\sim$10 mg/cm^2. The analysis which gave the lifetimes followed methods which have been described elsewhere.[29,30]

Precise determinations of the energies corresponding to the centroids of the lines as observed at 0° and 90° were made and used to calculate the observed average Doppler shift $\Delta E_{\text{obs}}=E(0°)-E(90°)$. The kinematic maximum for the average Doppler shift as observed at 0° is $\Delta E_{\text{max}}=(\langle v\cos\theta\rangle/c)E(90°)$, where $\langle v\cos\theta\rangle$ is the average value of the recoil-ion velocity projected onto the beam axis. This maximum shift was reduced by an attenuation factor $F(\tau)$ due to the slowing down of the Cl ions in the target. Thus the observed

[29] P. Paul, J. W. Olness, and E. K. Warburton, Phys. Rev. **173**, 1063 (1968); E. K. Warburton, J. W. Olness, and A. R. Poletti, *ibid.* **160**, 938 (1967); J. W. Olness and E. K. Warburton, *ibid.* **151**, 792 (1966).

[30] P. Paul, J. B. Thomas, and S. S. Hanna, Phys. Rev. **147**, 774 (1966).

TABLE III. Results of the attenuated-Doppler-shift measurements. Columns 3–5 refer to the parameters of the recoil Cl ions. $\Delta E_{\rm max}$ is the average value of the maximum Doppler-shift distribution and $\Delta E_{\rm obs}$ is the average value of the observed Doppler-shift distribution. The assignment of uncertainties to the mean lifetimes is discussed in the text.

Transition	E_γ (keV)	Maximum recoil angle (deg)	$\langle v\cos\theta\rangle$ (10^8 cm/sec)	θ (deg)	$\Delta E_{\rm max}$ (keV)	$\Delta E_{\rm obs}$ (keV)
^{35}Cl						
1219→0	1219	61.2	0.95	39	3.86	1.5
1763→0	1763	54.6	0.98	36	5.76	0.7
2646→0	2646	44.8	1.02	32	9.00	2.9
2646→1763	882	44.8	1.02	32	3.00	1.1
2695→0	2695	44.0	1.02	32	9.16	7.1
2695→1763	931	44.0	1.02	32	3.17	2.0
3002→0	3002	40.9	1.02	30	10.21	9.0
^{37}Cl						
1726→0	1726	54.0	0.98	36	5.64	2.5
3087→0	3087	39.5	1.02	30	10.49	8.0
$F_{\rm expt}$	τ (psec)	τ from other reports (psec)				
^{35}Cl						
0.39	$0.27_{-0.10}^{+0.19}$	$0.21_{-0.08}^{+0.10}$ [a]	0.3 ± 0.1 [b]	$0.13_{-0.02}^{+0.03}$ [c]		
0.12	$1.15_{-0.63}^{+0.45}$	0.55 ± 0.15 [a]	0.6 ± 0.2 [b]			
0.32	$0.35_{-0.07}^{+0.10}$	0.30 ± 0.09 [a]				
0.37	$0.29_{-0.13}^{+0.37}$					
0.78	0.062 ± 0.016	<0.03 [a]				
0.63	$0.115_{-0.059}^{+0.095}$					
0.88	0.031 ± 0.013	<0.05 [a]				
^{37}Cl						
0.44	0.23 ± 0.07	$0.17_{-0.05}^{+0.09}$ [d]	>0.04 [b]			
0.76	0.066 ± 0.015					

[a] Reference 33.
[b] Reference 34.
[c] Reference 36.
[d] Reference 35.

Doppler shift was

$$\Delta E_{\rm obs}=E(0°)-E(90°)=F(\tau)_{\rm obs}(\langle v\cos\theta\rangle/c)E(90°).$$

The procedure was to calculate the attenuation factor from theory, to get $F(\tau)_{\rm theoret}$ versus τ over the range $0\leq F(\tau)\leq 1$, and then to determine τ by comparison of $F(\tau)_{\rm obs}=\Delta E_{\rm obs}/\Delta E_{\rm max}$ with $F(\tau)_{\rm theoret}$. The theoretical values of $F(\tau)_{\rm theoret}$ were calculated[31] according to the method of Blaugrund,[32] which includes the effects of nuclear scattering as well as those of atomic and nuclear energy losses. The function $F(\tau)$ is plotted in Fig. 6 for recoil Cl-ion energy of 259.6 keV, which corresponds to a recoil velocity of 1.196×10^8 cm/sec. This velocity is within a few percent of each of the velocities in the average values $\langle v\cos\theta\rangle$ which were deduced as described in the next paragraph.

The calculation of the kinematic maximum of the average Doppler shift was carried out with the following considerations:

(1) The average incident proton energy was estimated to be 5.4 MeV. The target thickness was approximately 10 mg/cm^2; in this target the incident 5.6-MeV beam lost approximately 400 keV of energy.

(2) With this average beam energy of 5.4 MeV, the Cl recoil velocities versus laboratory angle θ were calculated for each excited level. For this endothermic (p, p') reaction, the velocity is a double-valued function restricted to angles $\leq 61.2°$ for the present cases.

(3) The assumption was made that the angular distribution of the recoil ions was isotropic in the c.m. system. The intensity in the laboratory system, $dI/d\theta$, was calculated.

(4) The intensity was converted to the intensity per unit of $v\cos\theta$, that is, $dI/d(v\cos\theta)$. For each excited level, this function was plotted versus $v\cos\theta$, since the Doppler shift is proportional to $v\cos\theta$. Each curve was a rather flat distribution extending over ~10 keV of energy. The average value of $v\cos\theta$ was extracted for each curve; these average values $\langle v\cos\theta\rangle$ and the shape of the distribution were very insensitive to changes in the assumed average incident proton energy. In Table III are listed the average values $\langle v\cos\theta\rangle$, the angle θ at which the average value occurs, and the maximum recoil angles.

From the observed Doppler shifts and the calculated kinematic maximum average Doppler shifts, the $F(\tau)_{\rm obs}$ were calculated, and then by comparison with Fig. 6, the values of τ were determined, as listed in Table III.

The major uncertainty in the determination of a value of τ rests in the determination of the $\Delta E_{\rm obs}$

[31] Through the cooperation of A. Tveter and colleagues at the Aerospace Research Laboratories, Wright-Patterson Air Force Base.

[32] A. E. Blaugrund, Nucl. Phys. 88, 501 (1966).

and the ΔE_{max}. A conservative estimate of the errors was made by assigning uncertainty of ± 0.5 keV to ΔE_{obs}, for each case, and propagating this uncertainty to give the listed uncertainties in the values of τ. The most difficult determination was that for the 1763-keV level, where the observed Doppler shift was a small one. The uncertainties in the values for τ in Table III overlap with those of other reported values.[33–36]

^{35}Cl

1219-keV Level

A triple angular correlation was taken at a proton energy of 4.65 MeV, at which energy there is a maximum in the yield of inelastically scattered protons at 180°. Other measurements[7–9,11] indicate that the spin-parity of this level is $\frac{1}{2}^+$. For a spin-$\frac{1}{2}$ level, the p-p'-γ correlation must be isotropic and will have no dependence on δ. The data are consistent with this requirement, being a straight line with a normalized χ^2 of 1.

The mean lifetime of 0.27 psec is in good agreement with another Doppler-shift value of 0.21 psec and with two bremmstrahlung resonance-absorption values of 0.13 and 0.3 psec (Table III).

1763-keV Level

Correlations of the p'-γ (1763) coincidences were obtained at $E_p = 4.74$ MeV for angles from 0° to 90° and at $E_p = 5.11$ MeV for angles from 31° to 90°. The γ-ray yield versus angle for both bombarding energies was nearly isotropic.

Spin-parity of $\frac{5}{2}^+$ has been assigned to this level from the evidence of a $P_4(\cos\theta)$ term in the angular distribution of γ rays emitted following the inelastic scattering of protons,[8] from the analysis of the angular distribution and cross section for the emission of γ rays following the inelastic scattering of neutrons,[11] and from the results from the angular distribution and polarization measurements[12] with the $(p, p'\gamma)$ reaction. Also, the J dependence[37,38] of the $l_p = 2$ angular distribution for the stripping reaction ^{32}S$(\alpha, p)^{35}$Cl establishes the spin-parity as $\frac{5}{2}^+$. The present results also indicate $\frac{5}{2}$ as the best choice. With spin-parity $\frac{5}{2}^+$, the range of $\delta(E2/M1)$, for which the χ^2 function has its minimum value of 0.6, is approximately $-\infty \leq \delta \leq -0.40$ and $+0.40 \leq \delta \leq \infty$. Outside of these regions, one or more of the fitting coefficients was negative and was set equal to zero before refitting. Reference 12 cites $\delta = 3.0 \pm 0.5$, and quotes from Hazewindus's thesis[7] $\delta = 2.7 \pm 0.4$. These values are not contradicted by the present analysis.

A search for a γ-ray cascade from this level showed that there exists only the transition to the ground energy level, with an upper limit of 3% on a possible but unobserved cascade through the 1219-keV level. This is in agreement with Hazewindus *et al.*,[7] who reported a 100% transition to the ground energy level.

The two other reported mean lifetimes of 0.55 and 0.6 psec are somewhat lower than the present value of 1.15 psec.

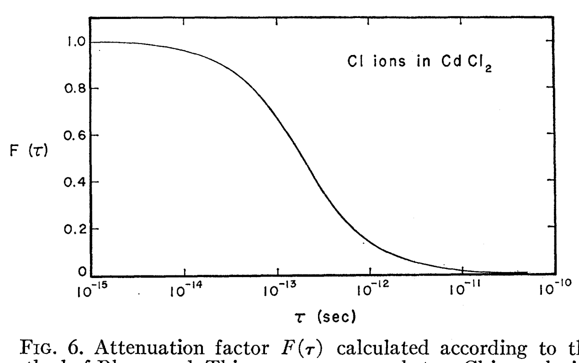


FIG. 6. Attenuation factor $F(\tau)$ calculated according to the method of Blaugrund. This curve corresponds to a Cl-ion velocity of 1.196×10^8 cm/sec.

2646-keV Level

A resonance for the production of the 2646-keV level, with protons scattered at 180°, was located at $E_p = 4.74$ MeV. At this same bombarding energy, the 2695-keV level was produced with intensity 0.316 of that of the 2646-keV level; this was determined by observation of the deexcitation γ rays emitted at 90° with a 15-cc Ge(Li) detector. With the annular detector, it was not possible to resolve the 2646- and the 2695-keV p' groups, and so the p'-γ(2646) correlation included a 24% contribution associated with the 2695-keV level. The presence of the $P_4(\cos\theta)$ term in the correlation $Y(\theta)$ requires that L or $L+1$ be equal to 2, and hence $J \geq \frac{5}{2}$. On the assumption that the 76% contribution from the 2646-keV level actually controlled the shape of the correlation, it is possible to interpret the χ^2 function graph. The spin of the 2646-keV level has been assigned[11] the value $\frac{7}{2}$; for this spin there are four limited regions of δ which satisfactorily fit the data. The parity of this level is predicted to be even.[21,22] The transition to the ground energy level, a $(\frac{7}{2}^+ \rightarrow \frac{3}{2}^+)$ transition, is expected to be an $E2$ transition, without observable $M3$ competition, and hence with $\delta(M3/E2) = 0$. At $\delta = 0$, Q^2 is 3.65, which indicates a compromise fitting to the data, probably caused by the admixture of 2695-keV radiation.

[33] F. Ingebretsen, T. K. Alexander, O. Häusser, and D. Pelte, Bull. Am. Phys. Soc. **14**, 125 (1969).
[34] E. C. Booth and K. A. Wright, Nucl. Phys. **35**, 472 (1962).
[35] J. J. Perrizo and G. I. Harris, Bull. Am. Phys. Soc. **13**, 1373 (1968).
[36] J. H. Hough and W. L. Mouton, Nucl. Phys. **76**, 248 (1966).
[37] T. Yamazaki, M. Kondo, and S. Yamabe, J. Phys. Soc. Japan **18**, 620 (1963).
[38] L. L. Lee, Jr., A. Marinov, C. Mayer-Boricke, J. P. Schiffer, R. H. Bassel, R. M. Drisko, and G. R. Satchler, Phys. Rev. Letters **14**, 261 (1965).

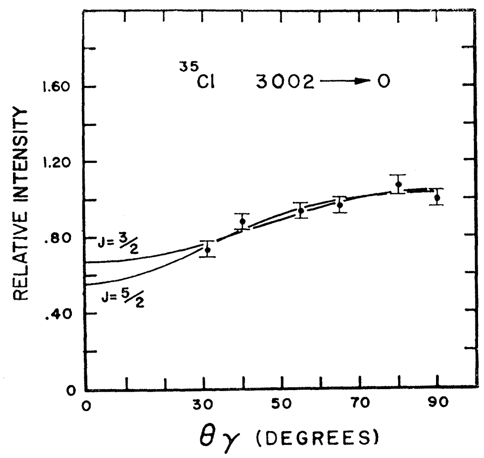


FIG. 7. Relative differential cross sections for the 3002-keV γ rays in coincidence with inelastically scattered protons at 180°.

The branching-ratio measurement was discussed earlier. The transitions consist of (85±3)% to the ground energy level and (15±3)% to the 1763-keV level. This result contradicts that of Ref. 7, which stated a 100% transition to the ground energy level, but it is in agreement with the $(n, n'\gamma)$ study.[11] According to the analysis, a (3±3)% transition to the 1219-keV level cannot be ruled out. The cascade γ ray for the transition (2646→1763) was observed in the Ge(Li) crystal-detector spectrum with energy 882.3±0.3 keV.

Of the two lifetimes in Table III, the 0.35 psec is to be taken as the more reliable one, with the cascade transition value of 0.29 psec serving as confirmation.

2695-keV Level

A resonance at 180° for the production of the 2695-keV level, with an accompanying low yield of the 2646-keV level, was not found, and it was not possible to obtain an angular correlation for this level. The branching-ratio measurement has been discussed earlier. The transitions consist of (79±3)% to the ground energy level, (14±3)% to the 1763-keV level, and (7±3)% to the 1219-keV level. This result contradicts that of Ref. 7, which reports 34% to the ground energy level and 66% to the 1219-keV level, but it is consistent with the $(n, n'\gamma)$ study.[11] The cascade γ ray for the transition (2695→1763) was observed in the Ge(Li) crystal-detector spectrum with energy 931.3±0.3 keV. The (2695→1219) cascade γ ray was also observed.

Glaudemans *et al.*[22] have assigned spin-parity $\frac{3}{2}^+$ to a predicted shell-model level at approximately this energy. The present γ-ray branching ratios are consistent with this assignment.

Of the two lifetimes given in Table III, the 0.062 psec is to be taken as the more reliable value, with the cascade transition value of 0.115 psec serving as confirmation.

3002-keV Level

Correlation data for the transition to the ground energy level were taken at 180° resonances at proton energies of 5.11 and 5.43 MeV. The p'-γ coincidence data at these two bombarding energies were not distinguishable from one another, so they were summed in order to reduce the statistical uncertainty; the result is shown in Fig. 7. The χ^2 function plot is shown in Fig. 8; it can be seen that permitted spins are $\frac{3}{2}$ or $\frac{5}{2}$, with rejection of spins $\frac{1}{2}$ and $\frac{7}{2}$. A tentative assignment of spin $\frac{5}{2}$ has been made by Taras *et al.*[15] with amplitude mixing ratio $0.05 \leq \delta \leq 0.10$. A larger value of δ is required by the present data, except at $\delta = 0$.

This level decays (97±1)% to the ground energy level and (3±1)% to the 1219-keV level. This branching was determined from a p'-γ coincidence spectrum which was obtained with the use of two NaI(Tl) crystals placed at 90° positions and with a counting period of many hours duration. The yield of cascade radiation was not large enough to permit the obtaining of an angular correlation for the cascade γ rays.

A predicted spin-parity-$\frac{5}{2}^+$ level at approximately this energy appears in the shell-model calculations.[22] An identification with the 3002-keV level would account for the last of the observed levels below 3163 keV, according to this model.

3163-keV Level

The p-p'-γ correlations for the (3163→0) transition were obtained at $E_p = 5.20$ MeV and at $E_p = 5.42$ MeV. Figure 9 shows Q^2 versus δ for the choice of

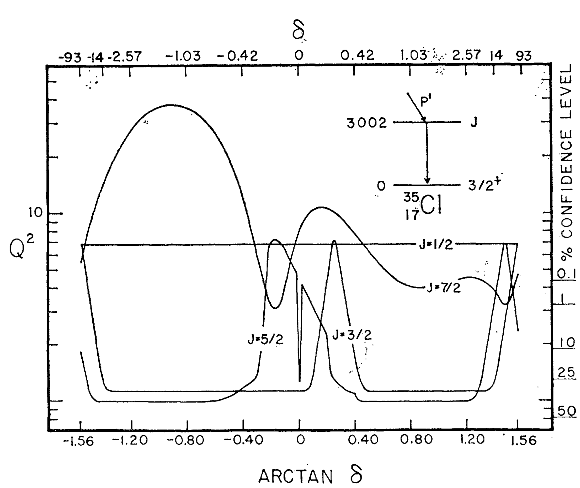


FIG. 8. Normalized χ^2 function Q^2 versus multipole amplitude mixing ratio δ for the (3002→0) transition in ^{35}Cl. Both $\frac{3}{2}$ and $\frac{5}{2}$ are acceptable choices.

$J=\frac{7}{2}$, since extensive studies of the $^{34}S(p,\gamma\gamma)^{35}Cl$ reaction have resulted in a firm assignment of spin-parity $\frac{7}{2}^-$ for this level. For the statistically more reliable data ($E_p=5.20$ MeV), the values of δ for which all three population parameters remain positive come in a limited range of -0.22 to -0.08, and justify the choice of $\delta(M3/E2)=-0.14_{-0.06}^{+0.08}$. This value is in good agreement with Watson *et al.*,[16] who give -0.16 ± 0.01, and Taras *et al.*,[15] who give -0.16 ± 0.05 and -0.25 ± 0.05.

The γ-ray branching for this level is $(79\pm5)\%$ to the ground energy level and $(21\pm5)\%$ to the 2646-keV level, as discussed earlier. An upper limit on transitions to the 1763-keV level is approximately 2%, which is consistent with a recently reported upper limit of 0.3% given by Wiesehahn and Prentice.[19] Previous branching results were 84 and 16% by Hazewindus *et al.*,[7] 90 and 10% by Watson *et al.*,[16] and 94 and 6% in Ref. 19.

The mean life of this level has been reported by Azuma *et al.*[18] as 140 ± 40 psec and by Ingebretsen *et al.*[33] as 40 ± 7 psec. The absence of an observable Doppler shift in the present work merely places a limit of $\tau\gtrsim7$ psec.

^{37}Cl

1726-keV Level

Correlations for the transition to the ground energy level were obtained at incident proton energies of 4.70 and 5.00 MeV, for which energies the yield of inelastically scattered protons showed maxima at 180°. The angular correlations at the two energies were both isotropic.

Recently, the mean lifetime of this level has been reported as $0.17_{-0.05}^{+0.09}$ psec.[35] The present result of 0.23 ± 0.07 psec is in good agreement.

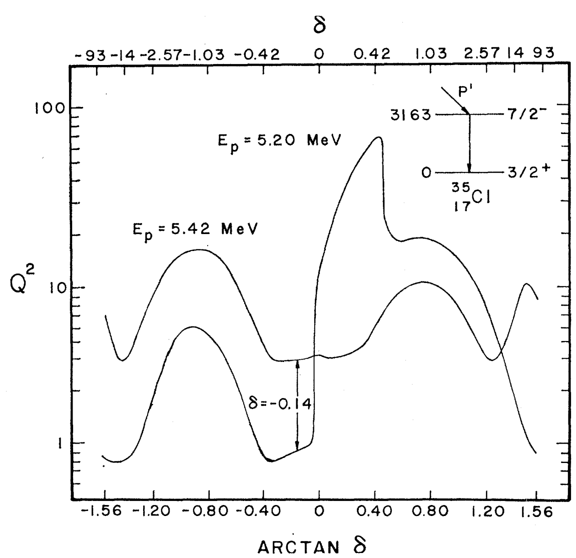


FIG. 9. Normalized χ^2 function Q^2 versus multipole amplitude mixing ratio δ. Considering all other experimental measurements, spin-parity $\frac{7}{2}^-$, with $\delta=-0.14$, is the preferred choice.

3087- and 3105-keV Levels

These closely spaced levels could not be resolved with either the proton detector or the NaI(Tl) γ-ray detector. However, it was known from the ^{37}S β-decay study[10] that the 3105-keV level decays 100% to the ground energy level, so that any observed cascade radiation in coincidence with unresolved inelastically scattered protons must necessarily be emitted from the 3087-keV level in a (3087→1726→0) cascade. A maximum in the yield at 180° of inelastically scattered protons with population of these levels was found at $E_p=5.29$ MeV. The coincident γ-ray spectrum contained no observable cascade radiation, and so it was not possible to obtain meaningful correlation data for either of the two levels. This absence of a cascade has been noted elsewhere.[20] Also, the possible 1361-keV γ ray from a (3087→1726) cascade was not observed in the spectrum as obtained with a Ge(Li) crystal detector.

The lifetime of the 3087-keV level, 0.066 ± 0.015 psec, is very close to that of the 3002-keV level of ^{35}Cl. The absence of an observable Doppler shift in the present work for the 3105-keV level merely places a limit of $\tau\gtrsim7$ psec on a lifetime, which is probably $\approx$100 psec, in analogy with the 3163-keV ^{35}Cl level.

V. DISCUSSION AND SUMMARY

As a result of this study, and of the studies of others, most of the low-lying levels of ^{35}Cl and ^{37}Cl have had measurements made of their energies, γ-ray branching ratios, and multipole mixing ratios, and for some levels their lifetimes for γ-ray emission. These results are summarized in the figures and tables, and especially in Fig. 1 and Tables I–III. A critical comparison of nuclear models of ^{35}Cl and ^{37}Cl is probably still not possible, but the present data together with data concerning other nuclei in the 2*s*-1*d* shell should permit this in the future.

Two comparisons of the existing data may be made—one with the levels of the mirror nucleus ^{35}Ar and one with the predictions of a shell-model calculation. ^{35}Ar, the mirror analog of ^{35}Cl, is expected to have nearly the same level structure as ^{35}Cl. Recently, Kozub[39] and Johnson and Griffiths[40] have reported on the neutron pickup reaction $^{36}Ar(p,d)^{35}Ar$, with the results shown in Fig. 10, where the angular momentum transfer l_n and the spectroscopic factor S for each transition are shown. The l_n and the spin-parity assignments are those of Kozub; he used the J dependence of the deuteron angular distributions to

[39] R. L. Kozub, Phys. Rev. **172**, 1078 (1968).
[40] R. R. Johnson and R. J. Griffiths, Nucl. Phys. **A108**, 113 (1968).

TABLE IV. Radiative widths and Weisskopf strengths for low-lying levels of ^{35}Cl and ^{37}Cl. Uncertain quantities are enclosed in parentheses. Where δ is unknown, both the electric and the magnetic multipole strengths have been calculated using the total width, in order to display the limiting values.

Nucleus and transition	$J_i^\pi \to J_f^\pi$	Branching ratio (%)	Multipole mixing ratio δ	Mean lifetime (psec)	Electric multipole L	Electric multipole Γ_γ (10^{-4} eV)	Electric multipole Strength $\lvert M \rvert^2 = \Gamma/\Gamma_W$	Magnetic multipole L	Magnetic multipole Γ_γ (10^{-4} eV)	Magnetic multipole Strength $\lvert M \rvert^2 = \Gamma/\Gamma_W$
^{35}Cl										
1219→0	$\frac{1}{2}^+ \to \frac{3}{2}^+$	100	...	0.24[a]	2	27.43[b]	185.7[b]	1	27.43[c]	0.073[c]
1763→0	$\frac{5}{2}^+ \to \frac{3}{2}^+$	100	3.0[d]	0.85[a]	2	6.97	7.46	1	0.77	0.0007
2646→0	$\frac{7}{2}^+ \to \frac{3}{2}^+$	85	(0)	0.33[a]	2	16.95	2.38	3	...	...
→1763	$\frac{7}{2}^+ \to \frac{5}{2}^+$	15	...		2	2.99[b]	101.6[b]	1	2.99[c]	0.021[c]
2695→0	$\frac{3}{2}^+ \to \frac{3}{2}^+$	79	...	0.062	2	83.87[b]	10.75[b]	1	83.87[c]	0.021[c]
→1219	$\frac{3}{2}^+ \to \frac{1}{2}^+$	7	...		2	7.43[b]	19.34[b]	1	7.43[c]	0.012[c]
→1763	$\frac{3}{2}^+ \to \frac{5}{2}^+$	14	...		2	14.86[b]	385.3[b]	1	14.86[c]	0.089[c]
3002→0	$\frac{5}{2}^+ \to \frac{3}{2}^+$	97	0.08[e]	0.031	2	1.32	0.099	1	204.6	0.037
→1219	$\frac{5}{2}^+ \to \frac{1}{2}^+$	3	(0)		2	6.37	6.44	3	...	...
3163→0	$\frac{7}{2}^- \to \frac{3}{2}^+$	84[a]	−0.16[f]	60[g]	3	0.0023	2.66	2	0.090	0.180
→2646	$\frac{7}{2}^- \to \frac{7}{2}^+$	16[a]	(0)		1	0.018[c]	1.8×10^{-5} [c]	2	0.018[b]	301.7[b]
^{37}Cl										
1726→0	$\frac{1}{2}^+ \to \frac{3}{2}^+$	100	...	0.20[a]	2	32.91[b]	36.37[b]	1	32.91[c]	0.031[c]
3087→0	$(\frac{5}{2}^+) \to \frac{3}{2}^+$	(≈100)	...	0.066	2	99.72[b]	6.02[b]	1	99.72[c]	0.016[c]
→1726	$(\frac{5}{2}^+) \to \frac{1}{2}^+$	<5	(0)		2	<4.99	<18.08	3	...	...
3105→0	$\frac{7}{2}^- \to \frac{3}{2}^+$	100	−0.18[h]	(≈60)[i]	3	(0.0034)	(4.05)	2	(0.106)	(0.225)

[a] Average value.
[b] Limiting value if $\delta = \infty$.
[c] Limiting value if $\delta = 0$.
[d] Reference 12.
[e] Reference 15.
[f] References 15 and 16.
[g] Reference 33.
[h] References 17 and 20.
[i] By analogy to ^{35}Cl 3163-keV level.

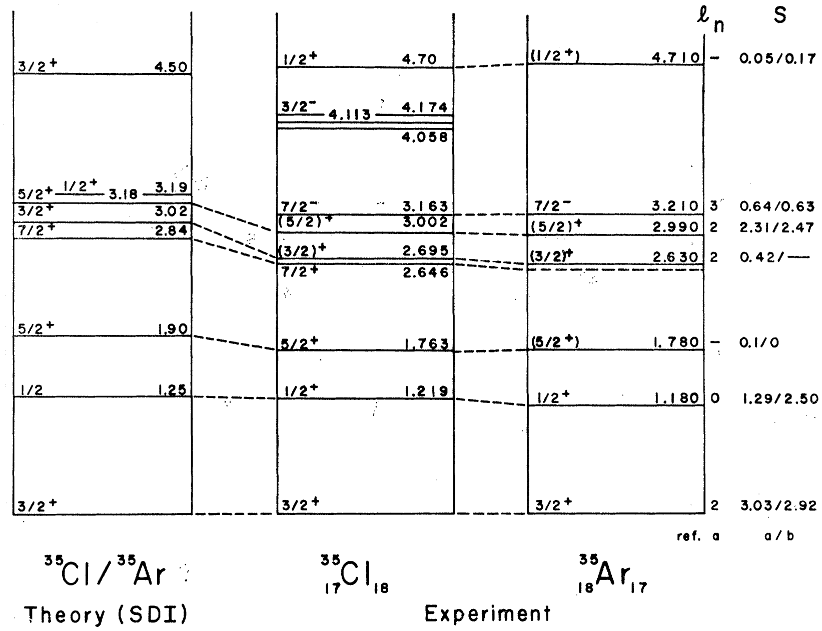


FIG. 10. Comparison of experimental energy and spin-parity data with predictions of the extended shell model (surface δ interaction) for ^{35}Cl and its mirror nucleus ^{35}Ar. The l_n and S for the neutron pickup reaction ^{36}Ar$(p, d)^{35}$Ar are from Refs. a (Ref. 39) and b (Ref. 40).

make a choice between $\frac{3}{2}$ and $\frac{5}{2}$ for the 2.99-MeV level. The weak transition to the 1.78-MeV $\frac{5}{2}^+$ level indicates that it is a result of a recoupling of the particle spins in a state which is not strong in the target ^{36}Ar; this transition was not observed by Johnson and Griffiths. The strong transition to the 2.99-MeV $\frac{5}{2}^+$ level indicates that it is due to the pickup of a $d_{5/2}$ neutron from the core of ^{36}Ar. The absence of a (p, d) transition to the analog of the ^{35}Cl $\frac{7}{2}^+$ level at 2646 keV supports its spin-parity assignment of $\frac{7}{2}^+$. Thus, these direct-reaction data substantiate the spin-parity assignments for the low-lying levels of the mirror analog ^{35}Cl. In Fig. 10 are shown also the predicted levels of ^{35}Cl resulting from the shell-model calculations of Halbert and collaborators[41]; the model used the surface δ interaction. The good agreement with the observed levels of ^{35}Cl and ^{35}Ar supports the assumptions on which this model is based. For ^{37}Cl, low-lying spin-parity-$\frac{1}{2}^+$ and -$\frac{5}{2}^+$ levels are predicted by this model at approximately the correct energies.

The odd-parity level in ^{35}Cl and the two odd-parity levels in ^{37}Cl are predicted by Erné's model,[23] which includes $f_{7/2}$ states.

Table IV contains a summary of the reduced widths and multipole strengths[42] which were calculated through use of all of the available data. Average values of the data were used in some cases, as noted. In the cases of transitions for which the electromagnetic multipole mixing ratio δ is not known, the reduced width and the strength for each multipole were calculated using the total width, in order to display the limiting values. Similarities of the three low-lying levels of ^{37}Cl to three corresponding levels of ^{35}Cl are to be noted. The first excited levels of spin-parity $\frac{1}{2}^+$ have normal $M1$ strengths[42] (assuming $\delta = 0$) of 0.073 and 0.031. If the transitions should be predominantly $E2$, then the $E2$ strengths are enhanced by factors of about 46 and 9 in contrast to the normal value of ~ 4 for this region. However, a small $E2$ admixture would result in a normal $E2$ strength without changing the $M1$ strengths very much from the tabulated values. The similarities of the 3163- and 3105-keV levels have been discussed in detail elsewhere[16,20]; the 3163-keV level exhibits a normal $M2$ strength and an $E3$ strength which is about 0.25 times that predicted by comparison with nearby nuclei.[42] If it is assumed that the 3105-keV level has the same lifetime as the 3163-keV level, the strengths for the two levels are nearly the same. The 3002-keV level of probable spin-parity $\frac{5}{2}^+$ and the 3087-keV level have nearly the same lifetimes, and consequently nearly the same $M1$ strengths (assuming that the 3087-keV level also decays by a predominantly $M1$ transition). The greatly inhibited $E1$ transitions from the 3163-keV level of ^{35}Cl, (3163→2646) and (3163→1763, not observed), are in accord with the trend in this part of the s-d shell.

ACKNOWLEDGMENTS

The assistance of Liong-Hien Liem and Jesse G. Mayes in the acquisition of data is gratefully acknowledged. The services of the staff of the University of Kentucky Computing Center were much appreciated.

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