the energy range 100–420 keV to be $(0.65\pm0.15)\times10^{-4}$ per 1*s* capture. This can be compared with the value 1.01×10^{-4} predicted by the theory for the same energy range. The experimental value is lower than the theoretically predicted value. This is not in disagreement with the previous measurements; in fact, all the measured average values[1,15] are systematically lower than the calculated ones. Additional and more accurate measurements of the magnitude of the internal bremsstrahlung intensity, especially for allowed transitions in light nuclei, are therefore necessary to determine the extent of the disagreement between theory and experiment.

[15] J. Zylicz, Z. Sujkovski, J. Jastrzebski, O. Wolczek, S. Chojnacki, and I. Yutlandov, Nucl. Phys. **42**, 330 (1963).

ACKNOWLEDGMENTS

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Properties of Cl^{34} Levels from the $S^{33}(p,\gamma)Cl^{34}$ Reaction

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Six resonances in the $S^{33}(p,\gamma)Cl^{34}$ reaction in the range $E_p=1.0$–1.3 MeV have been investigated in order to obtain information on resonance and bound-state properties of Cl^{34}. Revisions of previously reported γ-ray decay schemes of all six resonances were required as a result of measurements with a 40-cc Ge(Li) detector. The decay properties of 11 bound states below $E_x=4.0$ MeV were determined. Significant changes from previous results were found for the 0.665-, 3.545-, and 3.598-MeV levels. The 0.665-MeV level was observed to decay only to the ground state, as opposed to the branching ratio 80:20 for decay to Cl^{34} (0) and Cl^{34} (1) reported from earlier NaI(Tl) work. Transitions were observed from resonance levels to both the 3.545- and 3.598-MeV levels, which were unresolved in previous γ-ray work. The lower level was observed to decay only to the 0.147-MeV (3^+) level, while the upper level branches to the 0.147- and the 2.720-MeV level. Angular-correlation measurements at the 1165-keV resonance yield $J=3$ and 4, respectively, for the resonance and 2.376-MeV levels. The latter result is consistent with a previous prediction of $J^\pi=4^+$ from shell-model calculations. The $2.376\rightarrow0.147(3^+)$ transition is highly mixed dipole-quadrupole ($\delta=-6.3_{-3.2}^{+2.0}$) in reasonable agreement with a value $\delta=-2.7$ calculated with published wave functions. Angular distribution and strength measurements at the 1266-keV resonance yield $J^\pi=2^+$ and 1, respectively, for the resonance and 0.665-MeV levels. Similar measurements at the 1071-keV resonance yeild J^π (Res.) $=1^+$ or $2^\pm$. For several other levels, limitations on the possible spin assignments are obtained from transition speed considerations. Lower limits for the lifetimes of six bound states were obtained from Doppler-shift attenuation measurements at four resonances. New, more precise, values for the excitation energies of 12 bound states of Cl^{34} were obtained from Ge(Li) spectra. The $S^{33}(p,\gamma)Cl^{34}$ reaction Q value was found to be $Q=5140.3\pm1.5$ keV. This value is 15 ± 6 keV lower than the value $Q=5155\pm5$ keV given in the 1964 Mass Tables. The possible location of members of the $(d_{3/2}f_{7/2})$ odd-parity spectrum is discussed.

I. INTRODUCTION

SEVERAL recent theoretical investigations of the level structure of Cl^{34} have been published[1–3]; however, experimental information on energy-level properties is very meager. For example, the spins and parities of only the ground state 0^+ and first excited state 3^+ are firmly established, while 28 levels below $E_x=5$ MeV are known from (He^3, p), (α, d), and (He^3, α) data.[4] No resonance spin assignments are available. Most of the available information on properties of these levels results from the γ-ray decay-scheme work of Glaudemans *et al.*[5] with the $S^{33}(p,\gamma)Cl^{34}$ reaction. These measurements, however, were conducted with NaI(Tl) detectors and, considering the rather high-level density and the consequent complex γ-ray spectra, one may expect that many weak transitions were missed or that some transitions were unresolved.

* An element of the Office of Aerospace Research, U.S. Air Force.
[1] P. W. M. Glaudemans, G. Wiechers, and P. J. Brussaard, Nucl. Phys. **56**, 548 (1964).
[2] K. Sasaki, Nucl. Phys. **71**, 95 (1965).
[3] F. C. Erne', Nucl. Phys. **84**, 91 (1966).
[4] P. M. Endt and C. van der Leun, Nucl. Phys. **A105**, 1 (1967).
[5] P. W. M. Glaudemans, L. Eriksson, and J. A. R. Werkhoven, Nucl. Phys. **55**, 559 (1964).

TABLE I. Branching ratios of the γ-ray decay of $S^{33}(p, \gamma)Cl^{34}$ resonances in percent.

Resonance levels E_p (keV)[b]	E_x (MeV)[c]	Bound levels of Cl^{34} (E_x in MeV)[a] 0	0.147	0.462	0.665	1.229	1.886	2.158	2.376	2.581	3.545	3.598	3.982
1057	6.166	≤ 3	36 ± 6	≤ 2	≤ 2	6 ± 3	≤ 3	≤ 2	≤ 7	≤ 11	8 ± 4	14 ± 8	36 ± 9
1071	6.179	≤ 0.5	8 ± 4	6 ± 2	53 ± 4	13 ± 2	8 ± 2	3 ± 2	≤ 0.5	9 ± 2			
1096	6.204	≤ 1	≤ 2	≤ 3	≤ 1	≤ 1	≤ 2	≤ 4	≤ 4	≤ 4	31 ± 9	55 ± 11	14 ± 8
1165	6.271	≤ 0.6	≤ 4	≤ 0.8	1.0 ± 0.5	4 ± 1	9 ± 1	5 ± 3	81 ± 4	≤ 0.8			
1214	6.318	≤ 3	62 ± 7	7 ± 2	19 ± 3	≤ 3	≤ 5	≤ 4	≤ 3	12 ± 4			
1266	6.369	17 ± 2	15 ± 1	10 ± 1	44 ± 2	5 ± 1	≤ 1	≤ 2	≤ 1	9 ± 2			

[a] See Sec. III.
[b] These values are from Ref. 5.
[c] Resonance excitation energies are based upon the reaction Q value 5140.3 ± 1.4 keV determined in the present work (Sec. III).

Thus it seemed advisable to reexamine several of the more prominent $S^{33}(p, \gamma)Cl^{34}$ resonances with presently available high-resolution Ge(Li) detectors in order to obtain improved γ-ray decay sclemes, more precise level energies, lifetimes, and J^π values if possible.

In the following, we present the results of decay-scheme and strength measurements at six resonances in the region $E_p = 1.0$–1.3 MeV, level-energy and Q-value measurements, angular-correlation data at the $E_p = 1071$-, 1165-, and 1266-keV resonances, and the results of Doppler-shift-attenuation measurements at four resonances.

II. γ-RAY SPECTRA AND DECAY SCHEMES

The proton beam from the Aerospace Research Laboratory's 2-MeV Van de Graaff accelerator was used to produce the $S^{33}(p, \gamma)Cl^{34}$ reaction. The targets were prepared by evaporation of elemental S, enriched by 25.1% in S^{33}, onto 0.010-in.-thick Ag backings which had been earlier soldered to brass disks.[6] When in use, these targets were cooled by a stream of water directed at the backside of the brass disk. Such an arrangement permitted beam currents as high as 30 μA with no significant target deterioration.

The γ-ray spectra were obtained with a 40-cm^3 Ge(Li) detector located approximately 1 cm from the target and at an angle of 55° with respect to the proton-beam direction. The data were accumulated in a 4096-channel analyzer using standard electronics.

The six known resonances[4] at $E_p = 1057$, 1071, 1096, 1165, 1214, and 1266 keV were chosen for detailed study because of their relatively high strengths and their apparently interesting published decay-scheme properties. Singles spectra for each resonance were obtained in periods of 4 to 6 h. An example of one such spectrum obtained at the $E_p = 1266$-keV resonance is shown in Fig. 1. The decay schemes were derived from the known level energies and the relative photopeak and/or escape-peak intensities in the spectra. The energy dependence of the relative efficiencies was determined by a separate calibration of the detector using radioactive sources and selected simple decay schemes from other (p, γ) reactions. The intensity calibration thus obtained is estimated to be accurate to about 15% on a relative basis over the energy range of importance in these measurements.

The results of the analysis of the singles spectra are summarized in Tables I and II and in Fig. 2. At most resonances, transitions due to the $S^{34}(p, \gamma)Cl^{35}$ reaction were observed. Such transitions were most prominent at the $E_p = 1214$- and 1266-keV resonances. However, since the decay schemes of the competing S^{34} resonances are well known,[7,8] there was no difficulty in

[6] D. D. Watson, Rev. Sci. Instr. **37**, 1605 (1966).
[7] J. Dubois, Chalmers Tekn. Högsk, Handl. No. 266, 1963 (unpublished).
[8] D. D. Watson and F. D. Lee (to be published).

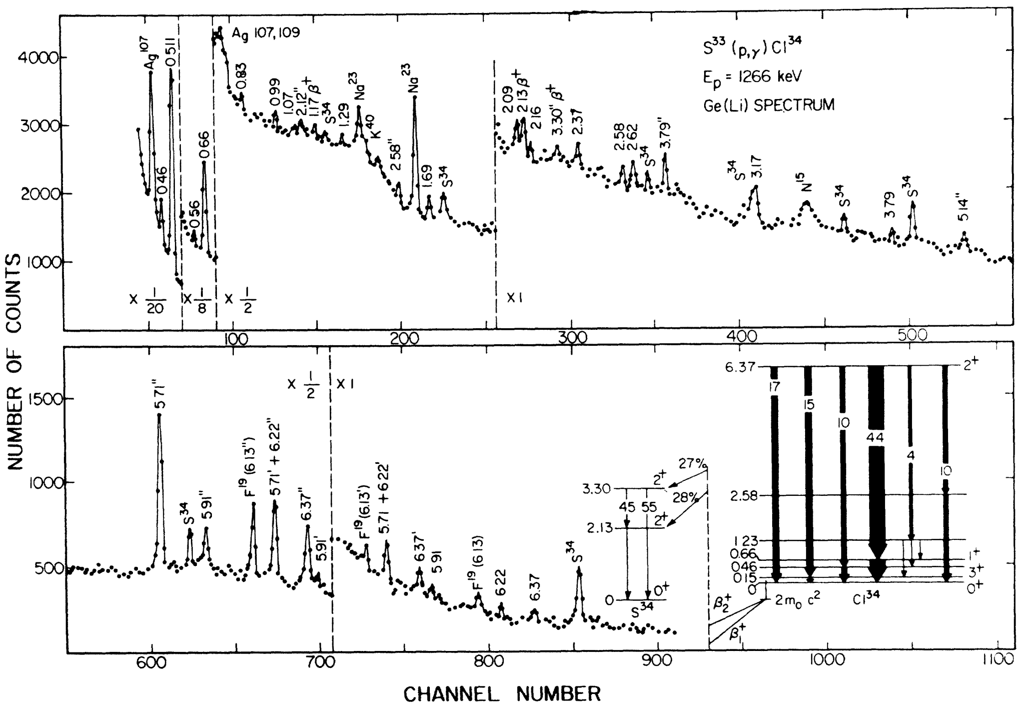

FIG. 1. Spectrum of γ rays observed at the $E_p=1266$-keV resonance with a 40-cm^3 Ge(Li) detector at $\theta=55°$. The corresponding Cl^{34} decay scheme is shown along with the transitions in S^{34} observed at this resonance due to β^+ decay of Cl^{34} (0.147). Double and single primes denote the double and single escape peaks, respectively.

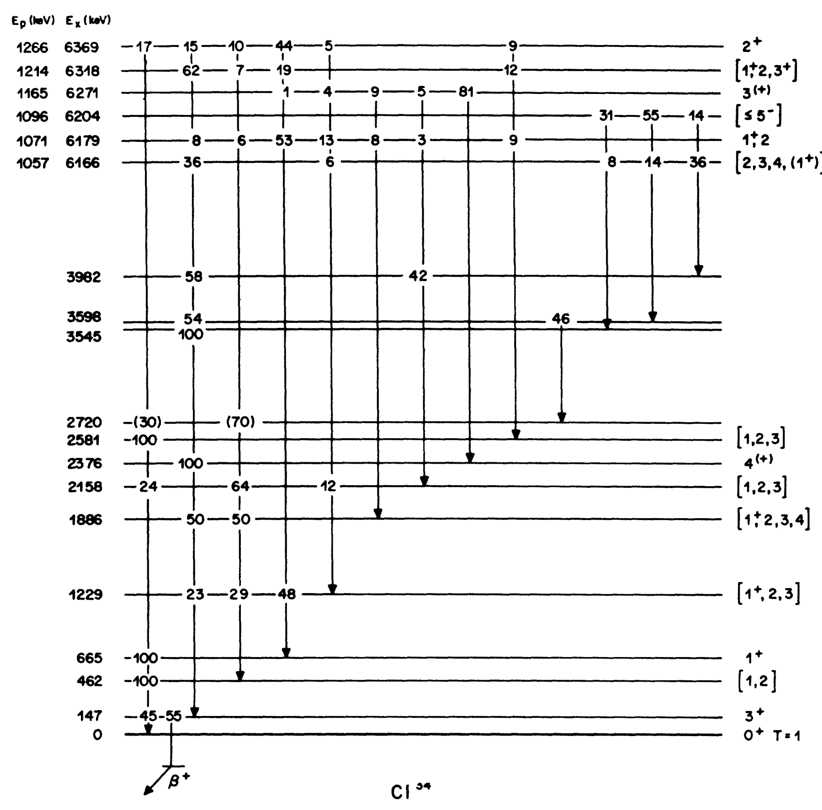

FIG. 2. Decay schemes of the resonance and bound levels of Cl^{34} as observed in this work. The indicated decay of the 2.720-MeV level is from Ref. 5. Upper limits on various other transitions are listed in Tables I and II. The unbracketed J^π values, except for Cl^{34} (0) and Cl^{34} (0.147), result from the angular-correlation and transition-strength data of this work (Sec. V). The bracketed values are from considerations of the observed transition rates, branching ratios, and limits on proton reduced widths (Sec. VI).

TABLE II. Branching ratios of the γ-ray decay of bound states of Cl^{34} in percent.

Initial state (MeV)	Final state (MeV) 0	0.147	0.462	0.665	1.229	1.886	2.158	2.376	2.581	2.720
0.147	100									
0.462	100	≤ 5								
0.665[a]	100	≤ 5	≤ 5							
1.229	≤ 2	23 ± 7	29 ± 5	48 ± 10						
1.886	≤ 8	50 ± 20	50 ± 18	≤ 8						
2.158	24 ± 9	≤ 6	64 ± 11	≤ 2	12 ± 4					
2.376	≤ 3	100	≤ 2	≤ 4	≤ 2					
2.581	100	≤ 8	≤ 15	≤ 6	≤ 6	≤ 8				
3.545	≤ 4	100	≤ 8	≤ 12	≤ 5	≤ 5	≤ 3	≤ 15	≤ 3	
3.598	≤ 8	54 ± 12	≤ 4	≤ 2	≤ 4	≤ 4	≤ 3	≤ 4	≤ 2	46 ± 7
3.982	≤ 3	58 ± 11	≤ 6	≤ 7	≤ 7	≤ 15	42 ± 10	≤ 7	≤ 7	

[a] See Sec. II G.

identifying and accounting for such transitions. Similarly, transitions due to other proton-induced reactions on C^{13}, N^{14}, N^{15}, F^{19}, Na^{23}, S^{32}, and $Ag^{107-109}$ were observed.

In the following, we comment briefly on the results at each resonance. In general, the results are in reasonable agreement with the earlier NaI(Tl) data of Glaudemans *et al.*[5] The changes from these earlier results due to the higher resolution of the Ge(Li) detector are noted.

A. 1057-keV Resonance

A transition with energy 3.985 MeV probably corresponds to a ground-state transition from the 3.98-MeV level. The transition energy does not agree with its previous assignment as a Res.$\rightarrow$2.16 transition. A previously unreported Res.$\rightarrow$1.23 transition was clearly observed. The Ge(Li) spectra show that a transition assigned earlier as a Res.$\rightarrow$3.55 decay is actually two transitions which correspond to resonance decay to both levels at $E_x=3.545$ and 3.598 MeV. These two transitions are much stronger at the 1096-keV resonance and are further discussed below.

B. 1071-keV Resonance

The results at this resonance are in very good agreement with the NaI(Tl) work of Glaudemans *et al.* One slight difference is an observed Res.$\rightarrow$0.462 transition not reported earlier. Relative intensity measurements in the present work suggest the presence of other unidentified transitions which feed the 0.462-MeV level.

C. 1096-keV Resonance

This interesting resonance shows no evidence of transitions to the lowest 13 levels of Cl^{34}. Only three primary transitions are observed, each of them to levels above $E_x=3.5$ MeV. [A previously reported transition to the 1.886-MeV level was not observed in Ge(Li) spectra.] As at the 1057-keV resonance, transitions to the two levels at 3.545 and 3.598 MeV were observed. However, both transitions are stronger at this resonance. Both levels clearly decay to the 0.147-MeV (3^+) level, but the relative intensity measurements indicate additional branching from the 3.598-MeV level. The presence of a 0.875-MeV γ ray at each of the 1057- and 1096-keV resonances, plus excellent relative intensity agreement, strongly suggest that the 3.598-MeV level decays to the 2.720-MeV level. Additional support for this assignment comes from the work of Glaudemans *et al.* in which an unexplained 0.88-MeV γ ray was found in all coincidence spectra at the 447-keV resonance. This resonance reportedly decays strongly to the "3.55-MeV" level. The decay of the 2.720-MeV level cannot be clearly determined from the present data, although there is evidence for a 2.720$\rightarrow$0.462 transition.

D. 1165-keV Resonance

The Res.$\rightarrow$0.147 transition previously reported at this resonance was not observed. However, such a transition may be obscured by the 6.13-MeV F^{19} γ ray. A new primary transition to the 1.886-MeV level was observed. The Ge(Li) data show that a rather large peak at 4.088 MeV cannot be a primary transition to the 2.158-MeV level. The origin of this γ-ray is unknown at present. The Res.$\rightarrow$2.158 transition does appear, but it is much weaker than reported from the NaI(Tl) data. An otherwise unexplained 3.66-MeV γ ray may be the primary member of a Res.$\rightarrow$2.61$\rightarrow$0.665 cascade for which the energies are in good agreement. Some uncertainty remains because additional intensity in the decay of the 2.61-MeV level is needed. Decay to the 2.61-MeV level was not observed at any of the 22 resonances studied in the NaI(Tl) work. *Note added in proof.* Additional measurements at this resonance made with higher target enrichment after submission of the manuscript confirm the presence of the 4.088-MeV γ ray and reveal an additional 2.035-MeV γ ray. These γ rays are probably members of a Res.→2.18→0.147 cascade involving a new level reported at $E_x = 2.179$ MeV by F. Brandolini, R. Engmann, and C. Signorini [Bull. Italian Phys. Soc. **71** (1969) and (to be published)]. Results given in the present paper concerning the nearby 2.16-MeV level remain valid.

E. 1214-keV Resonance

Previously unreported transitions from this resonance to the 0.462- and 2.581-MeV levels were observed. Relative intensity measurements suggest that there are probably several weak transitions from the resonance which ultimately feed the 0.462- and 0.665-MeV levels.

F. 1266-keV Resonance

The decay of this resonance was found to be more complex than observed in the NaI(Tl) work. An interesting new γ ray of surprisingly high intensity was identified as a Res.→0 transition. The presence of this decay mode strongly suggests $J=1$ or 2 for the resonance level, since transitions to the $J^\pi = 3^+$ and 1^+ states are also observed. (See Sec. VI.) Other new results at this resonance include primary transitions to the 0.462- and 1.229-MeV levels.

G. Decay of 0.665-MeV Level

A previous angular-correlation measurement by Smulders[9] at the 1266-keV resonance yields a probable $J=1$ assignment for the 0.665-MeV level. $J^\pi = 1^+$ is also strongly suggested by recent β^+-decay studies of Ar^{34} by Miller and Kavanagh.[10] The result $J=1$ was confirmed in the present work (Sec. V). For this assignment, it is rather difficult to explain on the basis of elementary transition-speed arguments the branching ratio 80:20 reported by Glaudemans *et al.* for the decay of the 0.665-MeV level to the 0^+ ground state and to the 3^+ level at 0.147 MeV. The $1^+ \to 3^+$ transition is expected to be much weaker, relative to the $1^+ \to 0^+$ transition, than indicated. For this reason it was felt that careful reinvestigation of the decay of this level with a Ge(Li) detector would be of value.

In Sec. III, new level energy measurements are given which show that the 0.147- and 0.665-MeV levels are separated by 518 ± 1 keV. Thus it is difficult to distinguish a possible transition between these two levels from the ever present 511.006-keV annihilation line. However, the relative intensity of the annihilation peak can be reduced considerably by coincidence techniques. Measurements were therefore performed at the 1057- and 1071-keV resonances in which Ge(Li) spectra were recorded in coincidence with transitions observed by an 8-in.-diam by 8-in.-long NaI(Tl) detector. The 1071-keV resonance decays strongly to the 0.665-MeV level, while the 1057-keV resonance decays to it weakly.

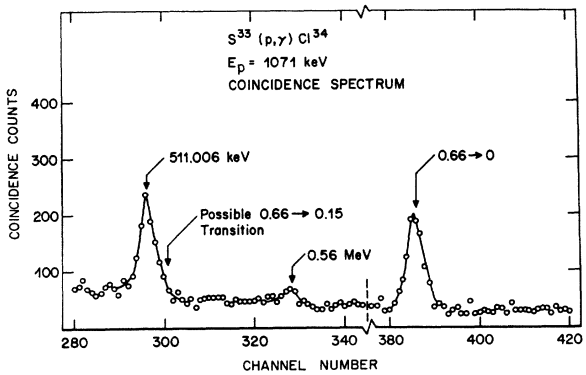

FIG. 3. Selected portions of the Ge(Li)-NaI(Tl) coincidence spectrum at the $E_p = 1071$-keV resonance. The arrow near channel 300 shows where a peak corresponding to a possible 0.66→0.15 transition would appear (see text).

It was found that the 0.665-MeV peak in the coincidence spectrum was reduced by a factor of four at the lower resonance, while the 0.511-MeV peak was unchanged in intensity. A more detailed numerical analysis of the relative intensities in the two spectra gave no indication of a 0.665→0.147 transition. The coincidence spectra are shown in Fig. 3 in which the expected position of the transition in question is indicated by the arrow. It can be seen that the detector resolution is such that the transition would cause a significant broadening on the high edge of the annihilation line. The analysis yields an upper limit of 5% for the intensity of the 0.665→0.147 transition relative to the 0.665→0 transition. The decay of the 0.665-MeV level is therefore consistent with the $J^\pi = 1^+$ assignment.

H. Resonance Strengths

The relative resonance strengths were derived, using essentially the same techniques described in Ref. 11, from measurements of thin-target (~2 keV) yield curves in the neighborhood of each resonance with the 8×8-in. NaI(Tl) detector located at 55° relative to the proton beam direction. The partial detection efficiency, or probability that a monoenergetic γ ray intercepted by the detector gives rise to a pulse with the correct amplitude to be transmitted by the window of the differential discriminator, was known from previous calibrations of the detector. For the present measurements, the discriminator window was set to accept pulses corresponding to the range $2.95 \le E_\gamma \le 7.0$ MeV. The over-all detection efficiency for the complete spectra

[9] P. J. M. Smulders, Utrecht University, 1965 (unpublished); (see Ref. 4.)

[10] R. G. Miller and R. W. Kavanagh, Phys. Letters **22**, 461 (1966).

[11] G. A. P. Engelbertink and P. M. Endt, Nucl. Phys. **88**, 12 (1966).

TABLE III. Strengths of resonances in the $S^{33}(p, \gamma)$ Cl^{34} reaction.

Resonance E_p (keV)	$(2J+1)\Gamma_p\Gamma_\gamma/\Gamma$ (eV)
1057	3.6±0.8
1071	3.5±0.6
1096	5.3±1.1
1119	1.0±0.3
1165	3.7±0.8
1214	2.3±0.5
1266	4.2±0.9

was obtained by adding the partial detection efficiencies of all lines in the spectrum, multiplied with their relative intensities.

The relative resonance strengths thus obtained were converted to absolute strengths by comparison with the known[11] strength, $(2J+1)\Gamma_p\Gamma_\gamma/\Gamma=21\pm3$ eV, of the 1211-keV resonance in the $S^{34}(p, \gamma)Cl^{35}$ reaction which could be observed using the same target. The results, including appropriate corrections for the known relative abundance ($S^{33}/S^{34}=9.2$), bombarding energy dependence, and the difference in target spins, are shown in Table III. The Table includes the 1119-keV resonance which was not otherwise studied in the present work.

The strengths obtained in this work are considerably higher than the values reported in Ref. 5, and, consequently, in the review article of Endt and van der Leun.[4] Part of the discrepancy (a factor of 1.5) results from an upward revision in Ref. 11 of the strength of the $E_p=580$-keV resonance in the $S^{32}(p, \gamma)Cl^{33}$ reaction used as calibration in Ref. 5. The origin of the remaining discrepancy (about a factor of 4) is not understood.

III. EXCITATION ENERGIES AND REACTION Q VALUE

The γ-ray spectra at each of the six resonances were calibrated by use of the 511.006-keV annihilation peak, the (6129.3±0.4)-keV γ ray from the $F^{19}(p, \alpha\gamma)O^{16}$ reaction,[12] and the energy difference between the full-energy and the second-escape peaks. The F^{19} γ ray appeared in all spectra. A computer program was used to fit the calibration data to a polynomial expression, and to correct for energy loss due to recoil where necessary. The most precise results were obtained for the 0.462-, 0.665-, and 1.229-MeV levels by careful measurement of the separation of the peaks corresponding to the transitions $0.46\to0$, $0.66\to0$, and $1.23\to0.46$ from the annihilation peak. Data from ten separate 1-h runs at the $E_p=1071$-keV resonance were used in this analysis. The energy of the 0.15-MeV level ($\tau_{1/2}=32$ min) was measured by observing the decay of the target following an extended bombardment period. In this case, calibration points were obtained from the well-known transitions from the decay of $Th(B+C+C'')$. In addition, the energies of the γ rays corresponding to transitions in S^{34} following β^+ decay of Cl^{34} (1) were measured.

At the 1266-keV resonance ($E_x=6.37$ MeV), a reasonably strong ground-state transition is present which, because of its nearness in energy to the F^{19} γ ray, was very useful for a determination of the reaction Q value. In addition, transitions to the (146.2±0.3)-keV level[4] from the $E_p=1057$- and 1214-keV resonances provided useful peaks very close to the 6.13-MeV F^{19} line. The data from these transitions, when combined with the results from cascades of the remaining resonances, provided an accurate determination of the Q value. The appropriately weighted result of the measurements at all resonances is $Q=5140.3\pm1.4$ keV. The primary source of error is the estimated uncertainties of ±2 keV in the resonance proton energies. This result is considerably lower (15±6 keV) than the value $Q=5155\pm5$ keV given in the mass tables.[13]

TABLE IV. Energies in keV of levels in Cl^{34} and of γ rays from S^{34}.

E_x (present work)	E_x (Ref. a)
Levels in Cl^{34}	
146.8±1.0	146.2±0.3
461.5±0.3	460±14
664.6±0.3	667±14
1228.8±0.7	1231±14
1885.9±1.6	1891±14
2158.4±1.2	2162±14
2375.6±0.7	2379±14
2580.6±1.3	2587±14
	2610±20
2720.4±1.6	2720±14
	3130±20
	3340±20
	3380±20
3544.6±1.3	3550±20
3598.4±1.2	3590±20
	3640±20
	3780±20
	3870±20
	3970±20
3982.0±1.1	3990±30
Transitions in S^{34}	
1176.5±1.4	1176.1±1.1
2127.6±0.8	2126.8±0.8
3304.9±2.3	3304.7±1.2

[a] Reference 4.

[12] J. B. Marion, Nucl. Data A4, 301 (1968).

[13] J. H. E. Mattauch, W. Thiele, and A. H. Wapstra, Nucl. Phys. 67, 32 (1965).

The excitation energies determined in this work are given in Table IV in which the results reviewed in Ref. 4 are also shown for comparison. In all cases, the quoted energies are weighted averages of measurements of two or more cascade γ rays involving the level in question. Also, in most cases the same level was measured at two or more resonances. The energies of γ rays in S^{34} arising from β^+ decay of Cl^{34} are also given in the table. The latter values are in agreement with the results of earlier measurements.

IV. DOPPLER-SHIFT ATTENUATION MEASUREMENTS

In an attempt to determine the lifetimes of some of the more strongly-populated bound states, Ge(Li) spectra were obtained at $\theta=0°$ and at either 115° or 120° for the resonances at $E_p=1057$, 1071, 1165, and 1266 keV. Relatively thick targets (25–30 keV) were used to insure that the recoiling ions stopped in the target material rather than in the Ag backing material. To compensate for possible gain drifts, the measurements consisted of many alternate short runs at forward and backward angles. The pairs of short runs were subsequently analyzed separately. Gains selected for these runs varied from 1.70 to 5.5 keV/channel.

Several techniques were investigated for the determination of the Doppler shifts from the data. These consisted of (a) least-squares fitting to the peaks to a Gaussian curve, (b) calculation of the peak centroid values, and (c) determination of the maximum in the convolution of a Gaussian curve with the experimental data. These calculations, as well as the error analysis, were performed by a computer. It was found that, for the most part, the shifts and associated errors were rather insensitive to the method employed. In several instances the peak in question was quite near an obviously unshifted peak (e.g., the 511-keV annihilation line or the 2127-keV γ ray following β^+ decay) which served as a useful check on the reliability of the results.

A computer program[14] based upon the slowing down theory of recoiling nuclei as elaborated by Blaugrund[15]

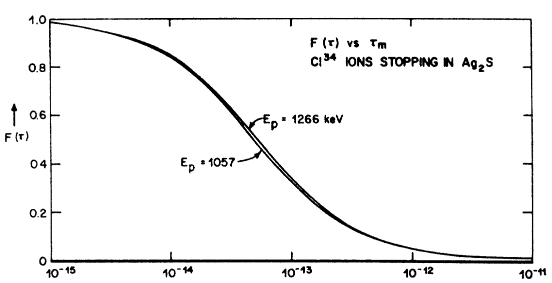

FIG. 4. Doppler-shift F, expressed as a fraction of the full shift, as a function of the mean life, for Cl^{34} ions stopping in AG_2S.

[14] The program used in this analysis was prepared by Dr. Audun Tveter.

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

TABLE V. Results of Doppler-shift attenuation measurements.

Resonance (E_p in keV)	Transition $E_x(i)\to E_x(f)$ (MeV)	F	τ_m (10^{-15} sec)
1072	0.66→0	0.00±0.07	≥280
1072	1.23→0.46	0.42±0.40	···
1072	2.16→0.46	0.07±0.29	≥27
1072	2.58→0	0.18±0.18	≥43
1057	3.98→2.16	0.02±0.18	≥78
1165	2.38→0.15	0.04±0.09	≥180

was used to determine the lifetimes from the observed attenuated Doppler shifts. The expected relationship between the mean life τ_m and the observed shift $F(\tau)$, expressed as a fraction of the total shift expected for infinitely short lifetimes, is illustrated in Fig. 4. A precise analysis of the Doppler-shift measurements was greatly hampered by the low yields and the low energies of the secondary transitions.

The Doppler shifts of γ rays from the levels at 0.66, 1.23, 2.16, 2.38, and 3.98 MeV were measured. The results were somewhat disappointing in that, within experimental errors, there was no positive evidence for Doppler shifts of any of the six analyzed γ-ray transitions. The results are summarized in Table V. The lower limits on the derived lifetimes correspond to twice the experimental errors in $F(\tau)$.

V. ANGULAR-CORRELATION MEASUREMENTS

The angular distribution of several γ-ray transitions from the resonances at $E_p=1071$ and 1266 keV were measured with the 40-cm³ Ge(Li) detector. The distributions were derived from spectra recorded at the angles 0°, 40°, 90°, and 115° relative to the proton beam direction. This set of angles was chosen so the same data could be used in the lifetime determinations discussed in Sec. IV. At the 1165-keV resonance, both angular-distribution and triple-correlation measurements were performed on the members of the prominent Res.→2.38→0.15 cascade. Independent measurements of the angular distribution, in this case at $\theta=0°$, 45°, and 90°, of the cascade members were obtained—one with the 8-in.-long by 8-in.-diam NaI(Tl) detector and one with the 40-cm³ Ge(Li) detector. The two sets of data thus obtained were in good mutual agreement.

The general experimental techniques and methods of data analysis used for angular correlations have been described previously.[16–18] The specific arrangement for the triple correlations used in the present work consisted of two 5-in.-diam by 5-in.-long NaI(Tl) detectors placed 5 in. from the target and the 8-in. detector

[16] G. I. Harris and D. V. Breitenbecher, Phys. Rev. **145**, 866 (1966).

[17] D. D. Watson and G. I. Harris, Nucl. Data **3**, 25 (1967).

[18] A. K. Hyder, Jr., and D. D. Watson, Aerospace Research Laboratories Report No. ARL-67-0168, 1967 (unpublished).

TABLE VI. Summary of angular-distribution measurements in the $S^{33}(p,\gamma)Cl^{34}$ reaction. (The resonance level is denoted by r.)

E_p	Transition	a_2 (Only)	a_2	a_4
1072	$r\to 0.15$	-0.26 ± 0.13	-0.24 ± 0.23	-0.02 ± 0.25
	$r\to 0.66$	-0.06 ± 0.05	-0.04 ± 0.07	-0.03 ± 0.09
	$r\to 1.23$	-0.06 ± 0.13	0.09 ± 0.19	-0.23 ± 0.24
1165	$r\to 2.37$	-0.01 ± 0.03	0.02 ± 0.03	-0.06 ± 0.04
	$2.37\to 0.15$	···	0.11 ± 0.03	-0.29 ± 0.04
1266	$r\to 0$	-0.18 ± 0.10	-0.21 ± 0.13	-0.03 ± 0.15
	$r\to 0.15$	0.11 ± 0.12	0.11 ± 0.13	0.00 ± 0.17
	$r\to 0.46$	-0.07 ± 0.14	-0.11 ± 0.16	0.09 ± 0.21
	$r\to 0.66$	-0.04 ± 0.05	-0.04 ± 0.06	0.00 ± 0.08
	$0.66\to 0$	0.28 ± 0.04	0.31 ± 0.05	-0.07 ± 0.07

placed 8 in. from the target. The 8-in. detector and one of the 5-in. detectors were movable in the horizontal plane through the proton beam axis. The third detector was movable in a vertical plane through the beam axis. Data were collected in "geometries" in which two of the detectors were fixed at $\theta=90°$ relative to the beam direction, while the third was successively placed at $\theta=0°$, 45°, and 90°. Pulses from the large detector corresponding to the γ-ray energy range from 3.0 to 4.0 MeV were used to gate both ADC's of the 4096-channel analyzer. Thus coincidence pulses from the smaller detectors were stored in separate 2048-channel subgroups of the analyzer memory. The triple-correlation measurements consisted of 17 separate 1-h runs with a beam current of 25 μA in order to accumulate a sufficient number of counts. Corrections for differing detector efficiencies and for asymmetries of the apparatus were obtained from separate measurements of the isotropic 2.37-MeV γ ray from the $C^{12}(p,\gamma)N^{13}$ resonance at $E_p=459$ keV. As an additional check, the angular distributions of the members of the well-known Res.$\to$3.16$\to$0 cascade at the $E_p=1211$-keV resonance[19] in $S^{34}(p,\gamma)Cl^{35}$ were measured.

The ground-state spin of S^{33} is $\frac{3}{2}$, so resonance formation with channel spins $s=1$ and 2 is possible. The magnetic substates of the resonance level which can be populated are thus restricted to $0\leq|m|\leq 2$. This restriction, plus the condition $\sum_m P(m)=1$, leaves in general two formation parameters to be determined from the data. Further restrictions on the ranges and relative values of the $P(m)$ can be obtained from the following relation[20] for formation with channel spin s with interfering orbital momenta l and l':

$$P_s(m)=(1+\epsilon_s^2)^{-1}[C_{sJlm}^2+2f\epsilon_s C_{sJlm}C_{sJl'm}+\epsilon^2 C_{sJl'm}^2], \quad (1)$$

where $C_{sJlm}=k(smJ-m\,|\,l0)$, and f is the Coulomb phase factor $\cos(\xi_l-\xi_{l'})$. The constant $k=1$ if $m=0$, and $k=\sqrt{2}$ if $m\neq 0$. The amplitude ratio of capture in channel s with momentum l' to capture with momentum l is given by ϵ_s. Where two channel spins are involved (as in the present case), the $P(m)$ are an incoherent mixture of the contributions from each channel s_1 and s_2. Thus,

$$P(m)=(1+t)^{-1}[P_{s_1}(m)+tP_{s_2}(m)], \quad (2)$$

where t is the intensity ratio of capture in channel s_2 to that in s_1. The relations (1) and (2) of course differ for different choices of resonance spin and parity.

Previously described computer programs[18] were used for least-squares analysis of the data over the allowable ranges of the population parameters and multipolarity mixing ratios δ for all choices of level spins and parities which are consistent with the observed transition speeds. The analysis yields the best set of parameters and the associated value of the goodness-of-fit parameter χ^2 for each spin sequence chosen. The programs accept as input data the measured values (and errors) of the intensity correlation at each angle, or set of angles (θ_1,θ_2,ϕ) in the case of triple correlations. Angular distributions are treated merely as special cases of the general triple correlations. For presentation purposes, however, the angular distribution data have been fitted in the usual way to a Legendre polynomial expression. The coefficients a_2 and a_4, after correction for finite size effects of the detector, are given in Table VI. The a_k are the coefficients in the expression $W(\theta)=\sum_k a_k P_k(\cos\theta)$, where the normalization is chosen such that $a_0=1$.

In the following we discuss the essential features of the analysis for each case in the order in which the main conclusions are best reached. The earlier assignments[4,21] of 0^+ and 3^+, for the ground and first excited states of Cl^{34} are assumed in the analysis.

[19] D. D. Watson, J. C. Manthuruthil, and F. D. Lee, Phys. Rev **164**, 1399 (1967).

[20] G. I. Harris, in *Nuclear Research with Low Energy Accelerators*, edited by J. B. Marion and D. M. Van Patter (Academic Press Inc., New York, 1967).

[21] P. Stähelin and P. Presiwerk, Nuovo Cimento **10**, 1219 (1953).

A. 1266-keV Resonance and 0.665-MeV Level

Resonance spin $J_R=0$ is excluded by the presence of the $(17\pm2)\%$ transition to the 0^+ ground state (Table I). The lower limit of the strength of this transition, as derived from the observed resonance strength and branching ratio, also excludes values $J_R\geq3$. In the case of $J_R^{\pi}=2^-$, this transition would be of the type $M2$ with a strength $|M|^2(M2)\geq80$ Weisskopf units (Wu).[22] Such an $M2$ strength is regarded as unreasonably high in relation to the empirical evidence[23] in $20\leq A\leq40$ nuclei, and in light of recent theoretical considerations.[24] For the choices $J_R^{\pi}=1^{\pm}$ and 2^+, reasonable transition rates are obtained. From the observed anisotropy of the Res.→0 and 0.665→0 transitions (Table VI), it is clear that there must be a significant $l=2$ contribution to the resonance formation if the parity is even.

We first consider $J_R=1$ in a more detailed analysis. The analysis of the Res.→0 angular distribution in this case involves only one parameter, since $\delta=0$. An acceptable fit to the data is obtained for the value $P(0)=0.45\pm0.07[P(1)=1-P(0)]$. This result is inconsistent, however, with the combined angular-distribution data on the members of the Res.→0.665→0 cascade. These data were analyzed for $J_R=1$ and the only reasonable choices $J(0.665)=1$, 2, and 3. The two parameters involved in this analysis are the multipolarity mixing ratio δ of the primary transition and the value of $P(0)$. For each choice of $J(0.665)$, acceptable fits to the data were obtained for unique values of δ and $P(0)$. But the values of $P(0)$ were 0.76 ± 0.06, 0.75 ± 0.06, and 0.71 ± 0.06 for $J(0.665)=1$, 2, and 3, respectively; each one of which is in clear disagreement with the value given above from the Res.→0 analysis.

For $J_R^{\pi}=2^+$, the analysis is more complicated because the resonance substates $m=0$, 1, and 2 all must be considered. However, the Res.→0 angular-distribution data are satisfactorily fitted in this case with the unique values $P(0)=0.13\pm0.10$, $P(1)=0.30\pm0.11$, and $P(2)=0.57\pm0.12$. Consider now the Res.→0.665→0 angular-distribution data for $J_R^{\pi}=2^+$. From Eqs. (1) and (2), a 2^+ resonance can be formed by $l=2$ capture in channel $s=1$, and by a mixture ϵ_2 of $l=0$ and $l=2$ capture in channel $s=2$. The data of this cascade were analyzed for the various choices of $J(0.665)$ and for successively chosen sets of $P(m)$ which satisfy Eqs. (1) and (2) for incremented values of t and ϵ_2. More specifically, for each choice of $J(0.665)$ and fixed set of $P(m)$, the curve of χ^2 versus δ was computed by the program and the minimum value of χ^2 noted. The process was then repeated for a new set of $P(m)$ corresponding to a new choice of t and ϵ_2. In this manner, a surface of minimum χ^2 values was generated

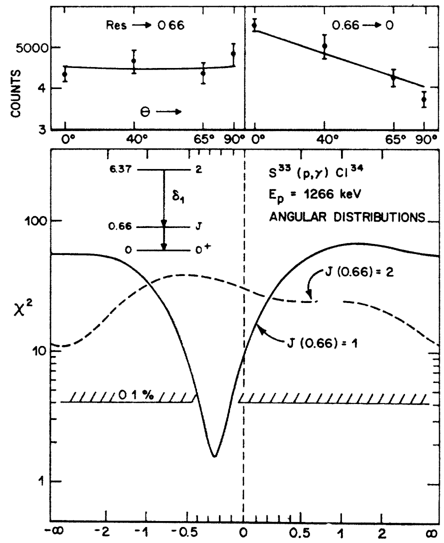

FIG. 5. Measured angular distributions and χ^2-versus-$\delta(R\rightarrow0.66)$ curves for the Res.→0.66→0 cascade at the $E_p=1266$-keV resonance. The lines through the data points represent the best fit for $J(0.66)=1$ and the resonance population parameters given in the text. The scale labeled θ is linear in $\cos^2\theta$. The data obtained at the angles labeled 65° were actually obtained at the equivalent angle of 115°.

for the range $0\leq t\leq\infty$ and $-\infty\leq\epsilon_2\leq\infty$. The values of δ_1, t, and ϵ_2 corresponding to the minimum point(s) in this surface thus represent the solution(s) for a particular $J(0.665)$. A choice for J is rejected if the minimum χ^2 point is above the 0.1% confidence "limit" for the data. We also require, of course, that the solution for ϵ_2 and t correspond to values of the $P(m)$ which are in agreement with the values given above for the Res.→0 angular-distribution data.

The results of the above analysis are as follows:

$J(0.665)$	χ^2 (min)
1	1.55
2	11.0
3	28.3

The 0.1% confidence limit is $\chi^2=5.4$, and thus $J(0.665)=1$ in agreement with the allowed character of the transition $Ar^{34}(\beta^+)Cl^{34}$ (0.665)[10] and an unpublished angular correlation result by Smulders.[9] The parameter values for this solution are $\delta=-0.21\pm0.11$, $P(0)=0.17\pm0.05$, $P(1)=0.19\pm0.08$, and $P(2)=0.64\pm0.05$. These values of $P(m)$ correspond to $t>10$ and $\epsilon=-1.4_{-1.6}^{+0.7}$ and are in good agreement with those given above for the Res.→0 angular-distribution data. The 2^+ resonance is thus formed primarily by channel spin 2 with a strong s-wave and d-wave admixture. The data and χ^2 curves for $J(0.665)=1$ and 2 are shown in Fig. 5. The appropriately weighted average values for the $P(m)$ are $P(0)=0.16\pm0.05$, $P(1)=0.21\pm0.07$, and $P(2)=0.63\pm0.05$.

[22] D. H. Wilkinson, in *Nuclear Spectroscopy*, edited by F. Ajzenberg-Selove (Academic Press Inc., New York, 1960), Part B.
[23] S. J. Skorka, J. Hertel, and T. W. Retz-Schmidt, Nucl. Data 2, 347 (1966).
[24] D. Kurath and R. D. Lawson, Phys. Rev. **161**, 915 (1967).

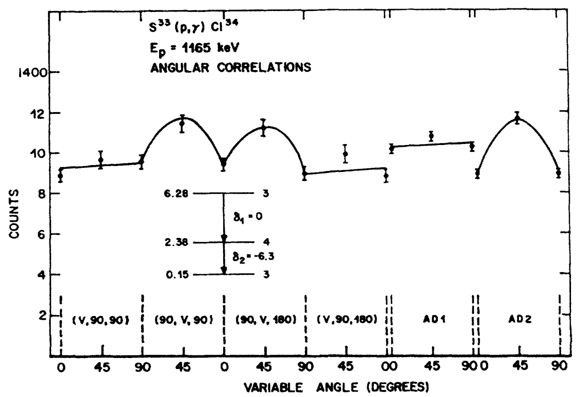

FIG. 6. Combined triple-correlation and angular-distribution data on the Res.→2.38→0.15 cascade at the E_p=1165-keV resonance. The lines through the data points represent the best least-squares fit for the indicated level spins and multipolarity mixing ratios. The horizontal scale is linear in $\cos^2\theta$.

For $J_R^\pi = 2^+$ and values of $P(m)$ varied over the error ranges just given, the Res.→0.147(3+) angular-distribution data were analyzed with the result $\chi^2 = 1.01$ and $\delta(R\to 0.147) = -0.11\pm 0.12$ or $\delta \geq 5$. In a similar manner, the data for the Res.→0.462 transition were analyzed for $J(0.462) = 1$, 2, and 3 with the results:

$J(0.462)$	χ^2	$\delta(R\to 0.462)$
1	0.19	-0.32 ± 0.12 or $\lvert\delta\rvert \geq 7$
2	0.36	0.20 ± 0.16 or $-5.0_{-18}^{+2.3}$
3	0.30	0.25 ± 0.18 or $2.3_{-0.9}^{+1.7}$

No choice for $J(0.462)$ can be made on the basis of these results. One obtains the conclusions: $J_R^\pi = 2^+$, $J(0.665) = 1$.

B. 1071-keV Resonance

The observed strengths of the Res.→0.147 and Res.→0.665 transitions result in octupole (or higher multipolarity) transition speeds greater than 10^3 Weisskopf units for values $J_R = 0$ or $J_R \geq 4$. For $J_R^\pi = 1^-$, the Res.→0.147 transition would be $M2$ with a strength $\lvert M\rvert^2 \geq 70$. Similarly, for $J_R^\pi = 3^-$, the Res.→0.665 transition would be $M2$ with $\lvert M\rvert^2 \geq 340$ if the 0.665-MeV level has even parity as indicated by the $Ar^{34}(\beta^+)Cl^{34}$ data.[10] For each of $J_R^\pi = 1^+$, $2^\pm$, or 3^+, reasonable transition rates are obtained.

Consider the possibility $J_R^\pi = 3^+$. The magnitude of the $M3/E2$ mixing ratio in this case for the Res.→0.665(1+) transition must be $\lvert\delta\rvert \leq 0.01$. Otherwise, the observed transition speed would lead to an $M3$ strength greater than 10 Wu. Therefore it is safe to assume that this transition is pure quadrupole in an analysis of the Res.→0.665 angular-distribution data for $J_R^\pi = 3^+$. The analysis, conducted with this restriction, does not yield an acceptable fit to the data. The minimum value of χ^2 was 45, which occurs for $P(0) = 0.61$, $P(1) = 0$, and $P(2) = 0.39$. The 0.1% confidence level is $\chi^2 = 6.8$.

No further limitations can be placed on J_R^π from the available data. For $J_R = 2$, the Res.→0.665 angular-distribution data can be fitted with $\chi^2 = 1.32$ and, for example, $\delta = 0$ and $P(0) = 0.15$, $P(1) = 0.54$, and $P(2) = 0.31$. These values, although not unique, correspond (for $J_R^\pi = 2^-$) to pure $p_{1/2}$ or pure $p_{3/2}$ capture with equal contribution from both channel spins; or (for $J_R^\pi = 2^+$) to $l = 2$ capture for $s = 1$ and $l = 0$ capture for $s = 2$ with $t = 3.2$. The Res.→0.147(3+) data can be fitted with the same set of $P(m)$. Similarly, for $J_R^\pi = 1^+$, the data for both transitions can be fitted with acceptable values of χ^2 for a variety of values of the $P(m)$ and mixing ratios. No additional information could be obtained from the Res.→1.23 angular-distribution data at this resonance. One obtains the following conclusions: $J_R^\pi = 1^+$ or $2^\pm$.

C. 1165-keV Resonance and 2.376-MeV Level

The data from the combined set of triple-correlation and angular-distribution measurements on the prominent Res.→2.38→0.147 cascade at this resonance are shown in Fig. 6. The various "geometries" are indicated by the fixed and variable angles of the set $(\theta_1, \theta_2, \phi)$.[16] $AD1$ and $AD2$ refer to the angular distributions of the primary and secondary members of the cascade, respectively. The evident, large $P_4(\cos\theta)$ term in $AD2$ (see also Table VI), could appear only if J_R and $J(2.38) \geq 2$. The resonance spin is also limited to values $J_R \leq 5$ because otherwise Γ_p would exceed the Wigner limit.

A least-squares analysis of the data was conducted over the entire ranges of the mixing ratios δ_1 and δ_2, and the $P(m)$, for all combinations of J_R and $J(2.38)$ subject to the above limitations and the condition $\lvert\Delta J\rvert \leq 2$ and $\lvert\Delta J\rvert \leq 3$ for primary and secondary transitions, respectively. $J = 3$ was assumed for the 0.147-MeV level as before. The χ^2 projection curves for

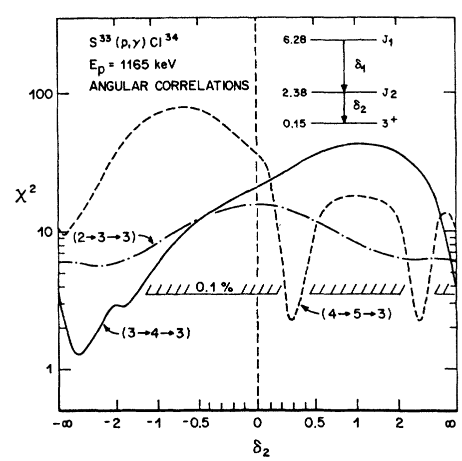

FIG. 7. Projection of the χ^2 surfaces on the (χ^2, δ_2) plane from the analysis of the data shown in Fig. 6. The curves are labeled by the assumed spin sequences. The 4→5→3 sequence can be eliminated by other considerations discussed in the text.

the spin sequences yielding the three best fits to the data are shown in Fig. 7. It can be seen that the $3\to4\to3$ spin sequence yields the best fit, although the $4\to5\to3$ sequence cannot be eliminated at the 0.1% confidence level. For both sequences, the primary transition (χ^2 curve not shown) is nearly pure dipole ($\delta_1=0.08\pm0.05$). For the $3\to4\to3$ sequence, the secondary transition is mainly quadrupole, $\delta_2=-6.3_{-3.2}^{+2.0}$. An additional analysis of the data was conducted for these two spin sequences by imposing the appropriate relations from Eqs. (1) and (2) on the values of $P(m)$. The result was that both 4^+ and 4^- resonance assignments agree equally well with the data ($\chi^2=1.95$). However, for $J=3$, even parity with $\chi^2=1.24$ is slightly favored over odd parity with $\chi^2=1.65$.

The possible $J=4$ resonance assignment is inconsistent with the observed strength of the Res.$\to$ $0.665(1^+)$ transition. From the resonance strength $(2J+1)\Gamma_p\Gamma_\gamma/\Gamma=3.7$ eV and the measured branching ratio (Table I), this transition would have strengths $|M|^2(E3)\geq1.0\times10^3$ and $|M|^2(M3)\geq3.2\times10^4$ for $J_R{}^\pi=4^-$ and 4^+, respectively. On the other hand, for $J_R{}^\pi=3^-$ or 3^+, the transition strengths would be $|M|^2(M2)\geq6.7$ or $|M|^2(E2)\geq0.18$, respectively. The latter value is in reasonable agreement with the empirical values for $E2$ transitions in neighboring nuclei.[23] The $M2$ strength is a little higher than might be expected.

Both the angular-correlation data and the transition-speed considerations favor even parity for the resonance level. The large dipole-quadrupole mixing of the $2.38\to0.147$ transition strongly suggests, but does not prove, even parity for the 2.38-MeV level. The possibility cannot be ignored that a large $E1$ inhibition could arise from the action of the $|\Delta T|=1$ selection rule for $E1$ transitions in self-conjugate nuclei. However, see Sec. VII. Conclusions obtained are $J_R{}^\pi=3^{(+)}$, $J(2.38)=4$.

VI. J^π LIMITATIONS FROM TRANSITION RATES

The J^π assignments from the preceding section, when combined with the decay scheme and strength data from Tables I–III, provide some useful limitations on the possible values of J^π for several levels of Cl^{34}. The arguments are similar to those used in some cases in the preceding section on angular correlations to eliminate assignments which would lead to highly unreasonable transition speeds. A brief comment is given in the following on each level for which J^π restrictions can be obtained from the available data.

A. 0.462-MeV Level

The strengths of primary transitions to this level from the $E_p=1071$- and 1266-keV resonances are consistent with any value $J(0.462)\leq4$. The observed ground-state decay ($\geq95\%$) of this level excludes $J=0$ and suggests the most reasonable values of J^π to be $1^\pm$ or 2^+. For the choices $J=3$ or 4, it would be difficult to explain the dominance of the ground-state (0^+) decay over the possible decay to the 3^+ level at 0.147 MeV. For example, in the most favorable case of 3^-, if the supposed $E3$ ground-state transition were enhanced to as much as 20 Wu, the possible $E1$ transition to the 3^+ level would still have a strength less than 6×10^{-12} Wu. The only reasonable values for the 0.462-MeV level are thus $J=1$ or 2.

B. 1.229-MeV Level

If $J(1.229)=0$, the primary transition to this level from the 1165-keV ($3^{(+)}$) resonance would have a strength of at least 9×10^3 Wu if $E3$, or higher if $M3$. Assuming the even-resonance parity assignment suggested in Sec. V is correct, we find that the choice $J^\pi(1.229)=1^-$ leads to an $M2$ strength of at least 40 Wu. If $E2$, this transition would have a reasonable strength of 1.2 Wu. For $J(1.229)\geq4$, the observed branching of this level to the $0.147(3^+)$ and $0.665(1^+)$ levels leads to very unreasonable relative transition strengths in analogy with the argument given above for the 0.462-MeV level. On the other hand, the values $J^\pi(1.229)=1^{(+)}$, 2, or 3 are all consistent with the available information.

C. 1.886-MeV Level

Considerations of the strength of the transition to this level from the 1165-keV resonance exclude the values $J^\pi(1.886)=0$ and 1^- for reasons parallel to those given above for the 1.229-MeV level. Values $J\geq5$ can be eliminated on similar grounds by consideration of the observed strength of the Res.$\to$1.886 transition at the 1071-keV (1^+, $2^\pm$) resonance. Thus $J^\pi(1.886)=1^+$, 2, 3, or 4.

D. 2.158-MeV Level

As above, the presence of a primary transition to this level from the 1165-keV resonance serves to eliminate the values $J^\pi(2.158)=0$ and 1^-. $J=0$ is also excluded by the presence of the $2.158\to0$ transition. Values $J\geq4$ are surely inconsistent with the strong branch (24%) to the 0^+ ground state. Thus $J^\pi(2.158)=1^+$, 2, or possibly 3. This level is believed to be the 2^+, $T=1$ analog of the 2^+ first excited state of S^{34} at 2.13 MeV.

E. 2.581-MeV Level

The 100% ground-state transition from this level eliminates $J=0$, and makes values $J\geq4$ highly unlikely. In addition, the primary transition to this level from the 1071-keV resonance would have a strength of at least 20 Wu if $E2$, or higher if $M2$. Thus the only reasonable assignments are $J=1$, 2, or possibly 3.

F. 6.166-MeV Level

The transition from this level, which corresponds to the $E_p=1057$-keV resonance, to the 3^+ level at 0.147 MeV would have an $E3$ strength $\geq10^5$ Wu, or an even higher $M3$ strength, if $J_R=0$. For $J_R^\pi=1^-$, this transition would be $M2$ with a strength ≥ 350 Wu. If $J_R^\pi=1^+$, the $E2$ strength would be ≥ 10 Wu. An $E2$ strength of 10 Wu, although higher than one may expect, is not sufficiently high to exclude a 1^+ assignment. This same transition would have an $M2$ strength ≥ 90 Wu for the choice $J_R^\pi=5^-$. The choice $J_R^\pi=5^+$ and higher values of J_R would lead to proton reduced widths in excess of the single-particle value. Since no further limitations can be deduced from the available data, we conclude $J^\pi(6.166)=2$, 3, 4, or possibly 1^+.

G. 6.204-MeV Level

The $E_p=1096$-keV resonance, which corresponds to this level, has a strength which would lead to proton widths in excess of the single-particle value for $J_R^\pi=5^+$ and higher values of J_R. No further limitations can be obtained from the data.

H. 6.318-MeV Level

This level corresponds to the $E_p=1214$-keV resonance. The strength of the transition to the 3^+ level at 0.147 MeV excludes values $J_R=0$ and $J_R^\pi=1^-$ for reasons parallel to those given above for the 6.166-MeV level. The Res.$\rightarrow$0.665(1^+) transition would have a strength ≥ 200 Wu if $M2$. Thus $J_R^\pi=3^-$ and higher values of J_R are not possible. This level therefore has $J^\pi=1^+$, $2^\pm$, or 3^+.

VII. SUMMARY AND DISCUSSION

The results of the present work are summarized in Fig. 2 and the tables. It was possible to obtain considerable improvement over previous decay-scheme information and level energies in Cl^{34} by use of a large Ge(Li) detector. Unique spin assignments were obtained for the bound levels at 0.665 and 2.376 MeV, and for the resonances at $E_p=1165$ and 1266 keV by angular-correlation techniques. Prior work had established only the spins of the ground and first excited states and a very probable assignment of 1^+ for the 0.665-MeV level.[4,9,10] The latter assignment was confirmed. Limitations on the possible J^π values for a number of other levels are discussed in Sec. VI and summarized in Fig. 2. The Doppler-shift attenuation measurements led only to limits on the lifetimes of five bound states (Table V). Future measurements, employing more highly enriched S^{33} targets than those presently available (25.1%), will undoubtedly yield improved lifetime data and make more comprehensive angular-correlation measurements possible.

The result $J=4$ obtained for the 2.376-MeV level agrees with the prediction of $J^\pi=4^+$ by Glaudemans *et al.*[5] based upon a comparison of the experimental level scheme with the shell-model calculations of Glaudemans, Wiechers, and Brussaard.[1] However, the 2^+ level calculated to lie at 1.49 MeV should now be identified tentatively with the 1.229-MeV level, or perhaps the 0.462-MeV level, instead of with the 0.665-MeV level now known to be 1^+.

The 2.376-MeV, $J=4$ level was found to decay by a highly mixed dipole-quadrupole ($\delta=-6.3_{-3.2}^{+2.0}$) transition to the 0.147-MeV, 3^+ level. This large mixing ratio suggests even parity for the 2.376-MeV level in agreement with the shell-model prediction. It is interesting to see if such a large mixing ratio will result from a detailed calculation using the wave functions obtained from the model calculations. It is easy to conclude from the published wave functions[1] that the $M1$-$E2$ mixing ratio may be large. The predominant component (78% in intensity) of the 3^+ level is of the type $|2s_{1/2}^4\,1d_{3/2}^2\rangle$, whereas the main component (83%) in the 4^+ level is $|2s_{1/2}^3\,1d_{3/2}^3\rangle$. The $M1$ matrix element vanishes between s and d orbitals while the $E2$ matrix element may not.

In order to perform the detailed calculations, we have adopted the phase-defined reduced matrix elements of Rose and Brink.[25] The reduction of the necessary many-particle reduced matrix elements, with explicit inclusion of isobaric-spin quantum numbers, in terms of the single-particle matrix elements of Rose and Brink was accomplished with standard techniques.[26] An advantage of this method lies in the fact that the sign of the computed mixing ratio, in addition to the magnitude, can be compared directly with experiment.[27] The formalism was developed in such a way that effective values of the nucleon charges and g factors can be explicitly introduced. The necessary coefficients of fractional parentage were taken from Ref. 1.

The calculated $M1$-$E2$ mixing ratio, expressed in terms of the effective proton charge $q_p=e_p/e$, neutron charge $q_n=e_n/e$, and proton and neutron g factors $g_{l,j}^p$ and $g_{l,j}^n$, is given by

$$\delta(E2/M1)=-0.686q^+/[g_{s1/2}^+-g_{d3/2}^+],$$

where $q^+=q^p+q^n$ and $g_{l,j}^+=g_{l,j}^p+g_{l,j}^n$. In the computation of the $E2$ matrix element, harmonic-oscillator wave functions were used to evaluate the radial integrals. The radial parameter was determined such that the expectation value $\langle r^2\rangle=R^2$, where $R=r_0A^{1/3}$ and $r_0=1.2$ fm.

The value of δ obtained by insertion of the free-nucleon values of the charges and g factors is -0.75. The corresponding mean lifetime of the 2.376-MeV level is 1.7 psec in agreement with the experimental limit $\tau_m\geq 0.18$ psec (Table V). For a more realistic comparison, we use the effective values $g_{s1/2}^p=2.68$, $g_{s1/2}^n=-1.12$, $g_{d3/2}^p=0.442$, and $g_{d3/2}^n=0.605$ obtained

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from the $2s_{1/2}1d_{3/2}$ calculations of Wiechers and Brussaard.[28] The mixing ratio is then $\delta=-1.35q^+$, which for free-nucleon charges yields $\delta=-1.35$. For the charges $q^p=1.5$ and $q^n=0.5$ obtained by Wilkinson[29] in a review of $1p$-shell data, one obtains $\delta=-2.69$ and $\tau_m=1.0$ psec.

As a check on the procedure and wave functions, we have also computed the width Γ_γ for the well-known $M3$ decay of the isomeric 3^+, $T=0$ level at 0.147 MeV. The result for this pure isovector transition is

$$\Gamma_\gamma(M3)=(5.85\times10^{-21})[4g_l^- - g_s^-]^2 \text{ eV},$$

where $g_l^-=g_l^p-g_l^n$, and $g_s^-=g_s^p-g_s^n$. For free-nucleon g factors, one obtains $\Gamma_\gamma(M3)=1.7\times10^{-19}$ eV in reasonable agreement[30] with the experimental value 1.1×10^{-19} eV derived from the lifetime $\tau_{1/2}=32.25$ min

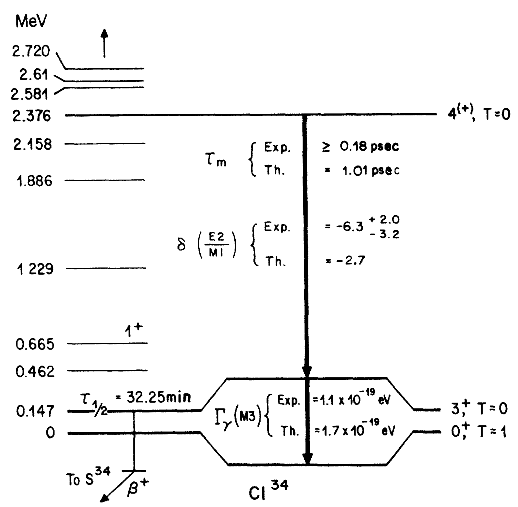

FIG. 8. Comparison of observed γ-ray decay properties of the 2.376- and 0.147-MeV levels of Cl^{34} with values computed from the shell-model wave functions of Ref. 1. Effective nucleon g factors and charges are taken into account as discussed in the text.

and branching ratio $\Gamma_\gamma/\Gamma_{\beta^-}=0.82$ given in Ref. 4. The shell model thus provides a good description of observed properties of the 3^+ and $4^{(+)}$ levels at 0.147 and 2.38 MeV in Cl^{34}. Figure 8 gives a schematic comparison of the calculated and experimental results.

The unusual decay of the $E_p=1057$- and 1096-keV resonances (Fig. 2) by strong transitions to the levels at $E_x=3.545$, 3.598, and 3.982 MeV resembles the characteristic $M1$ decay schemes of odd-parity analog levels observed recently in several neighboring nuclei including P^{30} and Ar^{38}.[31,32] It is not unlikely that the levels involved correspond to various members of the expected $(d_{3/2}f_{7/2})$, $T=0$ and 1, two-nucleon spectrum.[33,34] The decay of the 3.598- to the 2.720-MeV level suggests that the latter level is also a member of this odd-parity spectrum. Experimental support for this suggested character of these levels comes from the measurements by Dong-Hyok[35] of $S^{32}(\alpha,d)Cl^{34}$ spectra at $E_\alpha=29$ MeV. Strong d groups corresponding to Cl^{34} levels at $E_x=2.73$, 3.64, 4.06, 4.79, and 6.30 MeV (all approximately ±0.1 MeV) were observed. The first-four levels were tentatively identified as 2^-, 5^-, 3^-, and 4^- with dominant configurations $(d_{3/2}f_{7/2})$. The latter "level" may correspond to the 1057- and 1096-keV $S^{33}(p,\gamma)Cl^{34}$ resonances which lie near $E_x=6.2$ MeV. It is hoped that a more positive identification of these levels can be obtained in the near future with improved techniques and target enrichment.

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