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^{37}Cl(^{3}He,$\alpha\gamma$)^{36}Cl reaction: γ decay of the two lowest lying $T = 2$ states

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The ^{37}Cl(^{3}He, $\alpha\gamma$)^{36}Cl reaction was studied at 18 MeV, using an enriched CaCl$_2$ target. The γ rays coincident with the α particles emitted at forward angle were detected by two Ge(Li) detectors located at $\theta = 90°$ and 125°. Forty-two levels were observed in ^{36}Cl, essentially those seen in the (p,d) reaction. The γ-decay schemes of the two lowest lying $T = 2$ levels of ^{36}Cl (analogs of the first two levels of ^{36}S, $J^\pi = 0^+$ and 2^+, respectively) have been determined. The lowest $T = 2$ level at $E_x = 4299.5 \pm 1.1$ keV, feeds three levels: $E_x = 1165$ keV ($J^\pi = 1^+$, 65±8%), $E_x = 1601$ keV ($J^\pi = 1^+$, 28±5%), and $E_x = 2677$ keV ($J^\pi = 1^+$, 7±3%). The second one at $E_x = 7564 \pm 4$ keV feeds the levels at $E_x = 1601$ keV(42±6%), $E_x = 1960$ keV ($J^\pi = 2^+$, 40±6%), and $E_x = 2491$ keV($J^\pi = 2^+$, 18±4%). These decay schemes are compared with shell model predictions. Some other levels of ^{36}Cl are also discussed.

[NUCLEAR REACTIONS ^{37}Cl(^{3}He, $\alpha\gamma$), E = 18 MeV; measured $\sigma(\theta = 0°)$; γ-decay schemes of the two first $T = 2$ ^{36}Cl states deduced; Ge(Li) detectors; enriched target.]

I. INTRODUCTION

The first $(J^\pi, T) = (0^+, 2)$ levels in the $A = 4n$ and $T_z = 0$ and $+1$ s-d shell nuclei have been located in a simultaneous study[1] of the (p, t) and $(p, {}^3\text{He})$ reactions. Data on the electromagnetic decay mode of some of these states have been obtained[2,3] in the $T_z = +1$ nuclei ^{24}Na, ^{28}Al, and ^{32}P, by studying the γ rays in coincidence with the proton group feeding the first $T = 2$ level populated in the $({}^3\text{He}, p)$ reaction. In the $T_z = 0$ nuclei ^{20}Ne, ^{24}Mg, ^{28}Si, and ^{32}S, data have been obtained[4-7] by detecting the γ rays emitted after the formation of the first $T = 2$ level as an isospin forbidden resonance in proton or α-capture reactions.

Our aim has been to extend this study of the γ decay of the $T = 2$ levels to the $A = 36$ and $T_z = 0$ and $+1$ nuclei. The results summarized in the present paper concern the $T_z = +1$ nucleus ^{36}Cl and have been obtained using the ^{37}Cl(^{3}He, $\alpha\gamma$)^{36}Cl reaction which, starting from a $T = \frac{3}{2}$ target, permits feeding of $T = 2$ levels. The first $T = 2$ level (analog of the $J^\pi = 0^+$ ground state of ^{36}S) has been previously observed in several reactions: ^{38}Ar(p, ^{3}He)^{36}Cl,[1] ^{37}Cl(^{3}He, α)^{36}Cl,[8,9] and ^{37}Cl(p, d)^{36}Cl.[10,11] The most precise value for the excitation energy of this state $E_x = 4299 \pm 3$ keV has been obtained very recently[11] in a high resolution study of the (p, d) reaction which used a split-pole magnetic spectrograph. In the same study, the second $T = 2$ level (analog of the $J^\pi = 2^+$ first excited state of ^{36}S) has been identified at $E_x = 7557 \pm 6$ keV. This level had also been observed[9] using the $({}^3\text{He}, \alpha)$ reaction, as well as two other levels around 8.9 MeV for which a $T = 2$ assignment was also proposed. In these one-nucleon transfer reactions the attribution of $T = 2$ isospin is based upon excitation energy, transferred orbital momentum, and spectroscopic factor. No experimental data were available as yet concerning the γ decay of these $T = 2$ levels.

Additional information about the levels of ^{36}Cl can be found in a recent review article[12] by Endt and van der Leun. Results have been obtained with the transfer reactions already referred to, with other transfer reactions such as (d, p)[13,14] and (p, d),[15] with thermal neutron radiative capture reactions,[16-18] and with the ^{35}Cl($d, p\gamma$)^{36}Cl reaction.[19]

II. EXPERIMENTAL ARRANGEMENT

The ^{37}Cl(^{3}He, α)^{36}Cl reaction has been studied using an 18-MeV ^{3}He beam from the Orsay MP tandem. The target (180 ± 25 μg/cm^2) was prepared by vacuum evaporation of CaCl$_2$ (enriched to 96% in ^{37}Cl) onto a 20-μg/cm^2 carbon backing.

The γ rays were detected by two Ge(Li) detectors, 42 and 76 cm^3, located in the horizontal plane at $\theta = 90°$ and 125° with respect to the direction of the beam. In order to avoid undue loss of resolution, the counting rates were limited to 50 000 counts/sec by setting the detectors 10 cm from the target and reducing the beam intensity to 300 nA. The resolution was measured with a strong

^{60}Co source reproducing the experimental conditions of counting rate; it was 4.5 keV for the 1.33-MeV γ ray of ^{60}Co.

The efficiency curve for each of the detectors was obtained for $E_\gamma < 3.2$ MeV with a ^{56}Co source. For higher energies the efficiencies have been computed using the Monte Carlo method.[20] The accuracy of these efficiency curves is estimated to be about 10%.

The α particles emitted in the neighborhood of $\theta = 0°$ were focused, using a triplet of magnetic quadrupole lenses,[21] onto a 300-mm^2 1500-μm-thick Si(Li) detector. The detector was cooled by using the Peltier effect. This detection system does not yield the same solid angle for the whole energy spectrum. At the peak of the transmission curve the solid angle was equal to 15 msr. With the beam conditions used in this work the counting rate in the particle detector was 10000 counts/sec and the resolution was about 60 keV.

The linear electronics were maintained at constant temperature in order to improve stability. Gains were periodically checked during the experiment using a ^{56}Co source. The electronic timing utilized constant-fraction time pickoff units and a time-to-amplitude converter (TAC). Coincident events, characterized by several parameters (E_γ "42 cm^3," E_γ "76 cm^3," E_α, TAC output) were stored on magnetic tape and processed off line on the Orsay IBM 370-135 computer. After a correction which involved the particle energy versus time of flight relationship, the width [full width at half maximum (FWHM)] of the coincidence peak was reduced to about 5 ns.

III. RESULTS

A. Excitation energies of the observed levels

Forty-two ^{36}Cl levels have been observed in the present work. For most of them the energies have been obtained from the charged particle spectra. For some levels a more accurate value has been obtained from the associated γ-ray spectra.

1. Charged particles spectra

The α-particle spectra measured in coincidence with the γ rays detected in the 76-cm^3 detector are shown in Figs. 1 and 2. For the spectrum of Fig. 1 the current in the triplet lenses was adjusted so as to bring the α-particle group feeding the first $T = 2$ $E_x = 4.3$ MeV level to the maximum of the transmission curve. On this figure the α-particle group feeding the second $T = 2$ $E_x = 7.56$ MeV level also appears but the transmission is small for this group. A second measurement was made with magnetic conditions which bring this group to the maximum of the transmission curve (Fig. 2). The excitation energies of the ^{36}Cl levels were obtained with an accuracy of 15 keV using a calibration curve based upon the energies of the first two $T = 2$ levels, accurately measured in the present work (see Sec. III B), and the precise[12] energy of the level $E_x = 1960$ keV. There is a disagreement between our values and those obtained in a previous[9]

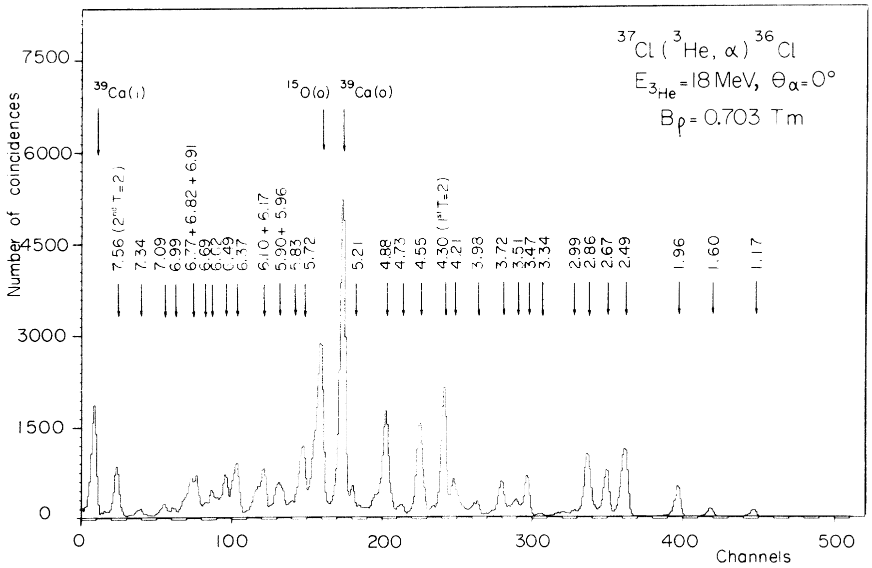

FIG. 1. Spectrum of α particles from the ^{37}Cl(^{3}He, α)^{36}Cl reaction measured in coincidence with γ rays detected in the 76-cm^3 Ge(Li) detector located at $\theta = 125°$ from the beam direction. With the indicated value of $B\rho$ (in Tm) obtained by adjusting the currents in the lenses, the α-particle group feeding the first $T = 2$ level, $E_x = 4.30$ MeV, is at the maximum of the triplet transmission curve.

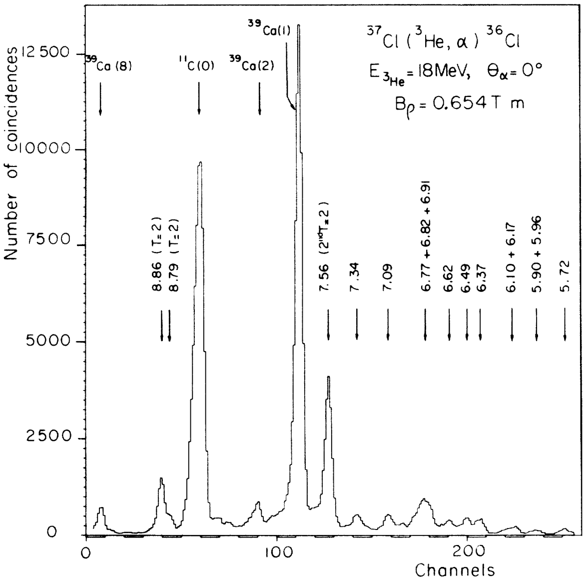

FIG. 2. Spectrum of α particles from the ^{37}Cl(^{3}He, α)-^{36}Cl reaction measured in coincidence with γ rays detected in the 76-cm^3 Ge(Li) detector located at $\theta = 125°$ from the beam direction. The current in the lenses was adjusted so as to bring the group of α particles feeding the second $T = 2$ level, $E_x = 7564$ keV, to the maximum of the transmission curve.

(^{3}He, α) study, especially for levels with $E_x > 4$ MeV. This difference, which can reach about 100 keV for the second $T = 2$ level, has been found to be due to an error in the computation (in Ref. 9) of the excitation energies from the calibration curve. After correction the energies from the two studies agree within error limits for the whole range of excitation energies.[22]

The two pickup reactions (^{3}He, α) and (p, d) feed essentially the same levels; most of the levels observed in the present work have been identified (Table I) with levels observed in the high resolution study[11] of the (p, d) reaction. The energy resolution of the Si(Li) detector does not allow resolution of ^{36}Cl levels separated by less than 50 keV; in some cases, however, the study of the associated γ-ray spectrum has permitted extraction of excitation energies of several levels unresolved in the particle spectrum. Such an example is presented in Fig. 3: in coincidence with what appears as a single α peak ($E_x = 2489$ keV, Fig. 1) γ transitions from three different levels at $E_x = 2467$, 2491, and 2519 keV are observed. These three levels are also clearly resolved in the recent[11] high resolution (p, d) study (Table I).

Because of the nature of the target, several groups of α particle from the (^{3}He, α) reaction on ^{40}Ca, the carbon of the backing, and an oxygen contamination, are also observed.

2. γ-ray spectra

A characteristic of these spectra is their low statistics. This is due partly to the experimental restrictions imposed on the γ-ray counting rate, and partly to the weak yield of the (^{3}He, α) reaction as compared to other γ-producing reactions. The γ-ray energy calibration was obtained from a second-order polynomial fit to various calibration data. These curves were obtained in several steps. First the centroids of the peaks corresponding to the annihilation radiation and to the ground-state transitions from the first four positive-parity levels of ^{36}Cl ($E_x = 789.2$, 1164.9, 1601.1, and 1959.6 keV, all ± 0.2 keV[12]) were used to get a calibration curve for energies $E_\gamma \lesssim 2$ MeV. The energies of escape peaks observed in this energy range and corresponding to ground-state transitions from ^{36}Cl and ^{39}Ca levels were then computed and the centroids of the total energy peaks used, together with the preceding data, to extend the calibration curve. Using this procedure it was possible to get a calibration curve up to $E_\gamma \approx 4.5$ MeV. The accuracy of the transition energy essentially depends on the accuracy of the centroid position. Precise values of the excitation energies of some levels obtained from transition energies determined in this way are given in Table I. The first two $J^\pi = \frac{1}{2}^+$ levels and the first $J^\pi = \frac{7}{2}^-$ level of ^{39}Ca have been observed in this work. Their measured excitation energies are in good agreement with previous determinations[12,23] (Table II).

B. $T = 2$ levels of ^{36}Cl

Only four of the six known[12] levels of ^{36}S up to 5 MeV are populated[24] in the proton pickup ^{37}Cl-(d, ^{3}He)^{36}S reaction. Due to the very simple relationship between the spectroscopic factors for proton and neutron pickup reactions to the analog levels $[C^2S_p = (2T+1)C^2S_n$, T being the target isospin$]$ four (and only four) $T = 2$ states of ^{36}Cl are expected to be populated appreciably in the neutron pickup reaction in the energy range $4 \leqslant E_x(\mathrm{MeV}) \leqslant 9$. The population of these four states can be accounted for by simple structure arguments. Even-parity levels can be generated as the coupling of four holes in ^{40}Ca $(1d_{3/2}\text{-}2s_{1/2})^{-4}$, and the four states fed by $l_p = 0$ or 2 transitions in the proton and pickup reaction also have this main configuration. The two remaining ^{36}S levels ($E_x = 3346$ keV, $J^\pi = 0^+$ and $E_x = 4193$ keV, $J^\pi = 3^-$) are not observed in the proton pickup reaction, this being probably due to dominant components in these

TABLE I. Excitation energies of ^{36}Cl levels observed through the ^{37}Cl(^{3}He, $\alpha\gamma$)^{36}Cl (present work) and ^{37}Cl(p,d)^{36}Cl reactions.

^{37}Cl(^{3}He, $\alpha\gamma$)^{36}Cl [a]		^{37}Cl(p,d)^{36}Cl [b]	^{37}Cl(^{3}He, $\alpha\gamma$)^{36}Cl [a]		^{37}Cl(p,d)^{36}Cl [b]
E_x [c]	E_x [d]	E_x	E_x [c]	E_x [d]	E_x
		0	4727		4738 ± 5
e		789 ± 1	4884		4884 ± 4
1165		1165 ± 1	5213		
1600		1600 ± 1			5702 ± 5
1960		1958 ± 1	5715		5734 ± 6
		2467 ± 1	5827		
2489 [f]	2491.2 ± 1.1	2491 ± 2	5902		5913 ± 5
	2518.9 ± 1.1	2517 ± 2	5955		5957 ± 5
2668	2676.9 ± 1.1	2675 ± 2	6097		6095 ± 5
	2812 ± 2	2799 ± 3	6172		6184 ± 5
2863 [f,g]	2862.4 ± 1.5	2863 ± 2	6374		6379 ± 5
2991		2995 ± 2	6486		6480 ± 7
3337		3331 ± 3	6621		6618 ± 5
3470	3471.0 ± 1.1	3470 ± 3	6681		6683 ± 5
		3566 ± 4	6771		6774 ± 6
3581		3598 ± 3	6823		6826 ± 6
3721	3725 ± 3	3722 ± 4	6900		6893 ± 7
3984		3990 ± 4	6998		7007 ± 6
4210		4205 ± 4	7085		7088 ± 6
4300		4299 ± 3	7339		
		4524 ± 4	7564		7557 ± 6
4547 [f]	4554 ± 2	4551 ± 4	8785		
		4720 ± 4	8859		

[a] Present work.

[b] Reference 11.

[c] Energy values are from the particle spectra (see Sec. III A 1). The accuracy is 15 keV except for the levels E_x = 1960, 4300, and 7564 keV taken as standards for the energy calibration of the particle spectra. The accuracy is 0.2, 1.1, and 4 keV, respectively, for these levels.

[d] Energy values are from the Ge(Li) spectra (see Sec. III A 2).

[e] The α-particle group feeding the first excited state at E_x = 789 keV of ^{36}Cl was not observed in the present work because of the triplet transmission curve.

[f] The associated γ-ray spectrum shows that several levels are actually populated even though only one peak is seen in the particle spectrum (Fig. 1).

[g] See Sec. III C.

states of configurations such as $(1d_{3/2}\text{-}2s_{1/2})^{-6}(1f_{7/2})^2$ and $(1d_{3/2}\text{-}2s_{1/2})^{-5}1f_{7/2}$, respectively, as suggested by their population in the ^{34}S(t,p)^{36}S reaction.[25]

1. E_x = 4300 keV level

The γ spectrum corresponding to the decay of the first $T = 2$ level is shown in Fig. 4. It was obtained using the 42-cm^3 Ge(Li) diode during a 34-h measurement (37 000 μC). Three transitions, to the E_x = 1165, 1601, and 2677 keV levels, have been identified. The measured energy of E_x = 4299.5 ± 1.1 keV is in very good agreement with the value of Ref. 11 reported in Table I. The measured relative intensities at $\theta = 90°$ and $125°$ are equal within error limits. This feature is consistent with the isotropic angular distribution expected for the γ decay of a $J^\pi = 0^+$ state.

We conclude that all the transitions with a relative intensity greater than 5% have been observed. The branching ratios are given in Fig. 5(a). From a comparison to theoretical analysis of ^{36}Cl it is reasonable, as will be discussed in Sec. IV, to identify the E_x = 1165, 1601, and 2677 keV levels with the three first $J^\pi = 1^+$ levels predicted[26,27] by shell-model calculations.

The $J^\pi = 1^+$ assignment for the E_x = 1601 keV level disagrees with the $J^\pi = 2^+$ value of Ref. 12 and will be discussed in Sec. IV. The identification of the E_x = 2677 keV level with the third $J^\pi = 1^+$ level in ^{36}Cl has been proposed previously[10,11] from a comparison of experimental spectroscopic factors with theoretical predictions.[26,27]

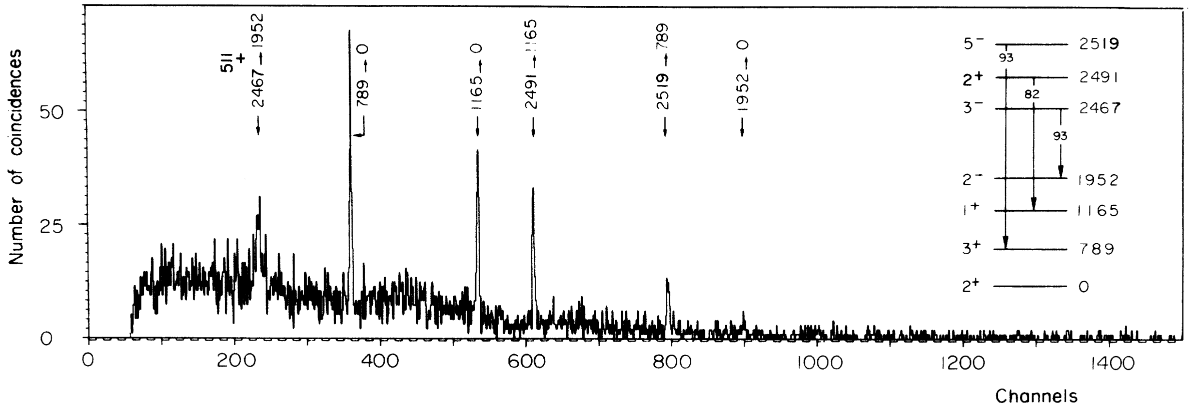

FIG. 3. γ-ray spectrum associated with the level at E_x =2.49 MeV (Fig. 1) obtained with the 42-cm^3 Ge(Li) detector at 90° from the beam direction. Transitions from the three levels with E_x =2467, 2491, and 2519 keV are observed. The width of the peak at channel 240 is due to the presence, in addition to annihilation radiation, of a 517-keV γ ray corresponding to the 2467→1952 transition. The decay scheme given in the figure is from Ref. 12 and the value $J^{\pi}=5^-$ for the level E_x=2519 keV is from Ref. 30.

2. E_x=7564 keV level

The γ spectrum from the second $T=2$ level is shown in Fig. 6. It was obtained with the 76-cm^3 Ge(Li) detector during a 16-h measurement (17000 μC). Three transitions to the levels E_x =1601, 1960, and 2491 keV have been identified. The excitation energy $E_x=7564\pm4$ keV was obtained from the double escape peak of the 7564 → 1960 transition which is in the range of validity of the γ-ray energy calibration curves. This value agrees with that of Ref. 11 given in Table I. The 4-keV error reflects the error on the position of the centroid and the inaccuracy of the calibration curve in this energy region. Transitions from this $J^{\pi}=2^+$ level to $J^{\pi}=1^+$ and 2^+ states can exhibit an $E2/M1$ mixing. However, since the $M1$ $\Delta T=1$ transitions are enhanced while the $E2$ $\Delta T=1$ transitions are typically retarded,[28] we have assumed that multipole mixing $\delta(E2/M1)$ is small. The branching ratios of Fig. 5(b) were accordingly determined from the spectrum measured at $\theta=125°$ (this angle being a zero for the second-order Legendre polynomial). We consider that all the transitions with a relative intensity greater than 10% have been observed.

The value $J^{\pi}=(1,2)^+$ has been assigned[12] to the E_x=2491 keV level. For reasons to be discussed (see Sec. IV) we propose the value $J^{\pi}=2^+$ for the E_x=2491 keV level, in agreement with Refs. 10 and 11.

3. E_x=8785 and 8859 keV levels

These levels, which appear in Fig. 2, correspond to the $l_n=0$ levels observed[9] at E_x=8.89 and 8.95 MeV (for the energy difference see Sec. III A 1); it was proposed[9] to consider these levels as the analogs of the $l_p=0$ levels of ^{36}S, observed[24] at E_x=4.52 and 4.58 MeV in the ^{37}Cl(d,^{3}He)^{36}S reaction. This assumption, partly based upon angular momentum and spectroscopic factor comparison between the proton and neutron pickup reactions, is substantiated by the fact that there is a quasiconstant difference (see Table III) between the energies of the four ^{36}Cl levels for which a $T=2$ assignment is proposed and the energies of the corresponding ^{36}S levels. Only one γ-ray transition, feeding the $J^{\pi}=3^+$ first excited state E_x=789 keV from the E_x=8859 keV level, was observed from these two levels. Decay modes other than electromagnetic are possible since these two levels are unbound: ^{35}S+p=7.97 MeV; ^{35}Cl+n=8.58 MeV; ^{32}P+α=7.64 MeV. The neutron and α emissions are isospin forbidden, but the proton emission is allowed.

TABLE II. Excitation energies of several ^{39}Ca levels observed in the ^{40}Ca(^{3}He, $\alpha\gamma$)^{39}Ca reaction.

E_x[a] (keV)	E_x (keV)	J^{π}[b]
2467.9±1.0	2467.0±1.0[c]	$\frac{1}{2}^+$
2797.6±1.3	2795.9±0.7[c]	$\frac{7}{2}^-$
4020.7±1.7	4017 ±9[b]	$\frac{1}{2}^+$

[a] Present work.
[b] Reference 12.
[c] Reference 23: ^{40}Ca(^{3}He, $\alpha\gamma$)^{39}Ca.

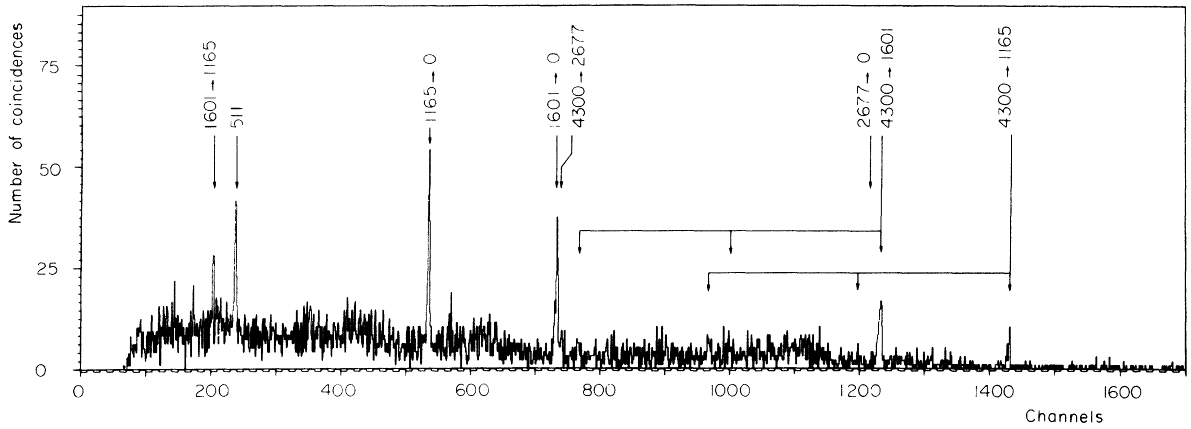

FIG. 4. γ-ray spectrum associated with the first $T=2$ level, $E_x=4.30$ MeV, obtained with the 42-cm^3 Ge(Li) detector at 90° from the beam direction.

C. Other ^{36}Cl levels

The transitions observed in this first study of the γ decay of some levels with $E_x > 4$ MeV are presented in Table IV. Weaker transitions may not have been observed. Except for the level with $E_x = 1601$ keV discussed in the next paragraph, the γ decay of levels with $E_x < 4$ MeV observed in the present work is in agreement with Ref. 12 within error limits.

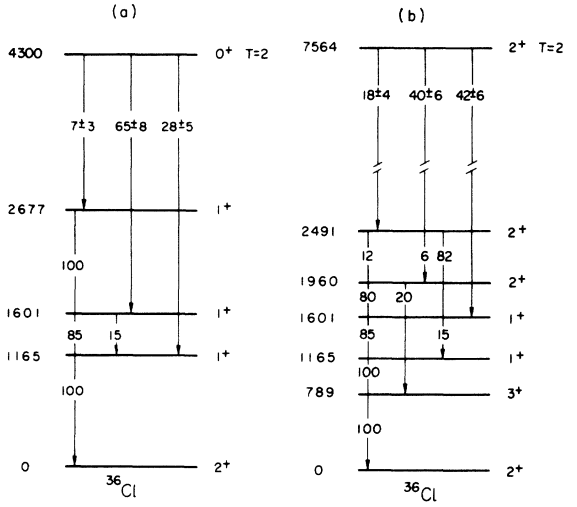

FIG. 5. Decay schemes of (a) the first $T=2$ level and (b) the second $T=2$ level. The excitation energies for $E_x < 2$ MeV are from Ref. 12, and from the present work and Ref. 11 for $E_x > 2$ MeV. The J^π values for the levels $E_x = 1601$ and 2491 keV are from the present work. For the other levels they are from Ref. 12. The branching ratios for the levels with $E_x = 1601$, 4300, and 7564 keV are from the present work; the other values are from Ref. 12.

1. $E_x = 1601$ keV level

The 436-keV transition 1601 → 1165 (previously observed in Ref. 17 but not quoted in Ref. 12) is confirmed. This transition can be seen in the γ spectra of the two lowest lying $T=2$ levels (Figs. 4 and 5) which strongly feed the level with $E_x = 1601$ keV. The relative intensities, from the γ spectrum associated with the $E_x = 1601$ keV level and measured at $\theta = 125°$, are 85% and 15% (±5%) for the ground-state and the 1601 → 1165 transitions, respectively.

2. $E_x = 2812$ and 2862 keV levels

These two levels cannot be separated in the particle spectrum. The weak population of the $E_x = 2812$ keV level is inferred from the observation of a weak $E_\gamma = 2023$ keV transition in the γ spectrum associated with the $E_x = 2862$ keV α peak of Fig. 1. This transition is interpreted as the known dominant transition 2812 → 789 keV.[12] The excitation energy (Table I, column 2) is in agreement with the value of Ref. 12, but disagrees with the result of the (p,d) reaction[11] where only one level at $E_x = 2799 \pm 3$ keV $l_n = 3$ is observed. The $J^\pi = 4^-$ value has been recently attributed[29] to the $E_x = 2812$ keV level in a study of the ^{33}S$(\alpha, p\gamma)^{36}$Cl reaction.

In the same γ spectrum a transition corresponding to the ground-state decay of the $E_x = 2862$ keV level is observed. A level with $l_n = 3$ (for which a $J^\pi = 3^-$ assignment was proposed) has been observed at $E_x = 2864 \pm 2$ keV in a study of the ^{35}Cl$(d,p)^{36}$Cl reaction[14]; a 100% ground-state transition was observed in a study of the ^{35}Cl$(d, p\gamma)^{36}$Cl reaction.[19]

On the basis of the mean differences between the energies of the negative-parity levels of ^{36}Cl and of their analogs in ^{36}Ar, the $E_x = 2864$ keV level

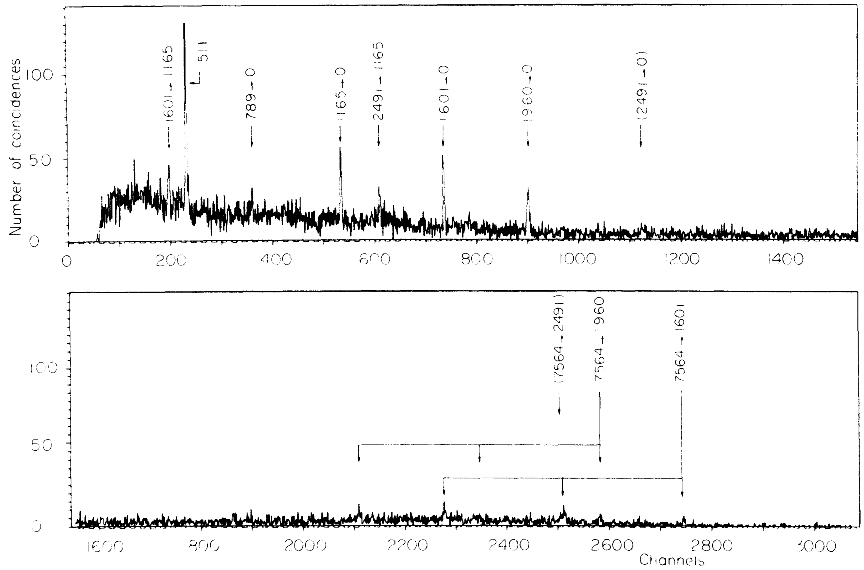

FIG. 6. γ-ray spectrum associated with the second $T=2$ level, $E_x=7564$ keV, obtained with the 76-cm^3 Ge(Li) diode at 125° from the beam direction.

was proposed[30] as the parent of the ^{36}Ar level $E_x=9.34$ MeV ($J^\pi, T=3^-, 1$) studied[31] in the $^{35}Cl(p,\gamma)$-^{36}Ar reaction. Moreover, a positive-parity level ($l_n=2$) is observed at $E_x=2863\pm2$ keV in the (p,d) reaction, leading to the hypothesis[11] of a doublet of levels. If one admits that the same levels are populated in the (p,d) and (^{3}He, α) reactions, our conclusion is that both members of the proposed doublet decay to the ground state.

3. $E_x=3725$ keV levels

Only one transition, to the $E_x=2812$ keV level with $J^\pi=4^-$, has been observed, in agreement with Ref. 19. Since the 3725-keV level is fed by $l_n=3$ transfer in the (p,d) reaction, values $J^\pi=(1$–$5)^-$ were proposed.[11] The measured[19] lifetime $\tau_m=70\pm15$ fs permits us to rule out the possibilities $J^\pi=1^-$ and 2^-, which would correspond to $M3$ and $E2$ strengths larger than 10^{10} and 10^3 W.u. (Weisskopf units), respectively. The allowed values of J^π correspond to $M1$ strengths of 0.60 $\pm$ 0.13 W.u. This level was proposed[30] as the parent of the ^{36}Ar $J^\pi=4^{(-)}$ $E_x=10.22$ MeV level, observed[31] in the $^{35}Cl(p,\gamma)^{36}Ar$ reaction.

IV. DISCUSSION

Shell-model calculations have been made for $A=36$ with a variety of model spaces and Hamiltonians. We discuss here the present experimental results, together with complementary data from other experiments, in a comparison with new theoretical results obtained with a comprehensive set of wave functions for the $A=32$–38 region.[26] These wave functions are calculated in the full sd-shell space with an empirically renormalized Hamiltonian. The features predicted for $A=36$ in

TABLE III. Comparison of parent and analog levels in ^{36}S and ^{36}Cl.

^{36}Cl E_x (keV)	^{36}S ^{a} E_x (keV)	J^π_ν ^{b}	Configuration (relative to ^{40}Ca)	E_x(^{36}Cl)-E_x(^{36}S) (keV)
4299.5 ± 1.1	0	0_1^+	$(1d_{3/2}\text{-}2s_{1/2})^{-4}$	4300
7564 ± 4	3291.0 ± 0.6	2_1^+	$(1d_{3/2}\text{-}2s_{1/2})^{-4}$	4273
	3346 ± 4	0_2^+	$(1d_{3/2}\text{-}2s_{1/2})^{-4}+(1d_{3/2}\text{-}2s_{1/2})^{-6}(1f_{7/2})^2$	
	4192.5 ± 0.7	3_1^-	$(1d_{3/2}\text{-}2s_{1/2})^{-5}1f_{7/2}$	
8785 ± 15	4523.0 ± 0.6	1_1^+	$(1d_{3/2}\text{-}2s_{1/2})^{-4}$	4262
8859 ± 15	4575.2 ± 0.7	2_2^+	$(1d_{3/2}\text{-}2s_{1/2})^{-4}$	4284

[a] The energies and J^π values are from Ref. 12.

[b] ν means the number of the level with a given J^π value.

TABLE IV. Transitions observed in the γ decay of several ^{36}Cl levels with $E_x > 4$ MeV.

E_x (keV) of the initial level		E_x (keV) and J^π values of the final level				
	E_x	0	789	1165	1960	2862
	J^π	2^+	3^+	1^+	2^+	*a*
4524		+				
4554		+			+	
4884				+		+
5702		+				
5734		+				
6095		+				
6146		+				
6184		+				
6379		+				
6771			+			
7085			+			
8859			+			

[a] Possibly a doublet of levels. See Sec. IIIC2.

TABLE V. Calculated excitation energies of the states of ^{36}Cl (Ref. 24).

E_x (MeV)	J^π	ν [a]	E_x (MeV)	J^π	ν [a]
0.000	2^+	1	7.758	4^+	4
0.927	3^+	1	7.819	5^+	2
1.100	1^+	1	7.934	0^+	3
1.640	1^+	2	8.222	4^+	5
1.767	2^+	2	8.495	4^+	6
2.397	2^+	3	8.581	0^+	4
2.424	3^+	2	8.676	5^+	3
2.792	1^+	3	9.629	5^+	4
3.151	0^+	1	9.680	0^+	5
3.361	1^+	4	9.935	5^+	5
3.411	4^+	1	10.297	6^+	2
4.020	3^+	3	10.795	0^+	6
4.200	2^+	4	11.527	5^+	6
4.559	2^+	5	12.450	6^+	3
4.851	1^+	5	12.614	7^+	1
4.919	3^+	4	13.220	6^+	4
5.044	2^+	6	13.866	7^+	2
5.110	3^+	5	14.013	6^+	5
5.421	1^+	6	15.571	6^+	6
5.590	4^+	2	15.610	7^+	3
5.850	4^+	3	19.057	8^+	1
6.056	3^+	6	20.525	7^+	4
6.666	0^+	2	21.881	7^+	5
6.849	6^+	1	24.792	7^+	6
7.328	5^+	1			

[a] ν means the number of the level with a given J^π value.

this new work are quite similar in most respects to the results published in Ref. 27.

The energies for $A = 36$ states obtained in the shell-model calculation are listed in Table V. Electromagnetic transition rates were calculated from the associated wave functions with the assumptions of a bare-nucleon $M1$ operator and an $E2$ operator derived from the assumptions of $e_p = 1.5e$, $e_n = 0.5e$, and $\hbar\omega = 12.1$ MeV. The results for various observables in ^{36}Cl are presented in Tables VI–XI, together with the relevant experimental data.

The electric quadrupole moment of the 2^+ ground state of ^{36}Cl is -1.68 $e$fm^2 (Ref. 12), while the present calculation yields -2.76 $e$fm^2. Both numbers are small, a manifestation of the theorem that $E2$ moments for states corresponding to a half-full orbit are zero. The dominant component of the wave function thus contributes nothing to the calculated moment, the total coming from the small amplitude admixtures. Correspondingly, the calculated answer is sensitive to the details of the calculation, and we note that the result of Ref. 27 is as much too small as the present result is too large. The calculated magnetic dipole moment of $+1.34\mu_N$ is in reasonably good agreement with the measured value of $+1.285\mu_N$ (Ref. 12).

The mean life of the $E_x = 789$ keV $J^\pi = 3^+$ first excited state is calculated to be 29 ps, with about 75% of the strength coming from the highly retarded $B(M1)$ of $0.0029\mu_N^2$ and 25% from the $B(E2)$ of 25 e^2fm^4. The calculated mixing ratio $|\delta| = 0.6$ must be compared with the experimental value δ

TABLE VI. Decay of the $E_x = 1601$ keV level (J_ν^π, $T = 1_2^+, 1$); $\tau_m = 800 \pm 150$ fs, Ref. 19; $\tau_{\text{calc}} = 2300$ fs.

Final level		Branching ratio (%)		Calculated transition strengths and widths			
J_ν^π, T	E_x (keV)	Expt. [a]	Calc.	$B(M1)$ (μ_N^2)	$\Gamma(M1) \times 10^5$ (eV)	$B(E2)$ (e^2fm^4)	$\Gamma(E2) \times 10^5$ (eV)
2_1^+, 1	0	85 ± 5	47	0.0015	7.1	7.6	6.5
1_1^+, 1	1165	15 ± 5	53	0.16	15.3	21.6	0.03

[a] This work.

TABLE VII. Decay of the $E_x = 1960$ keV level ($J^{\pi}_{\nu}, T = (2_2)^+, 1$); $\tau_m = 60 \pm 15$ fs, Ref. 19; $\tau_{\text{calc}} = 34$ fs.

Final level		Branching ratio (%)		Calculated transition strengths and widths			
J^{π}_{ν}, T	E_x (keV)	Expt. [a]	Calc.	$B(M1)$ (μ_N^2)	$\Gamma(M1) \times 10^4$ (eV)	$B(E2)$ (e^2fm^4)	$\Gamma(E2) \times 10^5$ (eV)
2^+_1, 1	0	90	97	0.21	183	30.6	71
3^+_1, 1	789	10		0.0015	0.3	0.6	0.1
1^+_1, 1	1165		2	0.056	3.3	0.9	0.02
1^+_2, 1	1601		1	0.50	2.7	18	0.01

[a] Reference 12 and present work.

$= -1.1 \pm 0.4$ of Ref. 12. The calculated lifetime is in good agreement with the experimental results of Ref. 32 ($\tau_m > 5$ ps) and Ref. 33 ($\tau_m = 30 \pm 1$ ps), but is much longer than the result of Ref. 19 ($\tau_m = 3 \pm 1$ ps). Some doubt on the last value has been remarked previously.[12]

The decay of the $E_x = 1165$ keV $J^{\pi} = 1^+$ level to ground state is calculated to be dominated by a $B(E2)$ of 53 e^2fm^4 which competes with a very small calculated value of $B(M1)$: 0.0002 $\mu_N{}^2$. The deduced mixing ratio $|\delta| = 5$ is in disagreement with the experimental value $\delta = 0.32 \pm 0.06$ of Ref. 12. The resulting calculated mean life of 6.4 ps is, however, in good agreement with the experimental result ($\tau_m = 7.1 \pm 0.5$ ps) of Ref. 33, but slower than the result ($\tau_m = 3 \pm 1$ ps) of Ref. 19.

The feeding of the $E_x = 1601$ keV level by $l = 0 + 2$ transitions in transfer reactions limits the J^{π} possibilities to $(1, 2)^+$. The $J^{\pi} = 2^+$ assignment of Ref. 12 to this level seems to be essentially based upon the results of a study of the ^{37}Cl(p, d)^{36}Cl by Vignon, Longequeue, and Towner[15] who proposed this value by comparing their experimental spectroscopic factors with the theoretical ones obtained through various calculations. But, since the completion of the compilation of Ref. 12, two other investigations of the ^{37}Cl(p, d)^{36}Cl reaction were reported[10,11] in which the comparison of experimental and theoretical spectroscopic factors did not allow a clear-cut J^{π} assignment to the 1601-keV state. However, the identification of this state as the second 1^+ rather than the second 2^+ seems favored from these later analyses. With the $J^{\pi}_{\nu} = 1^+_2$ assignment to this level, moreover, the level sequence of ^{36}Cl up to $E_x = 2$ MeV is in good agreement with the calculated one (Table V) and the experimental branching ratios for the decay of the first $T = 2$ level are well reproduced by the calculation (see below and Table X). This would not be the case with the $J^{\pi}_{\nu} = 2^+_2$ assignment. In summary, it is our conclusion that the assignment of 2^+ in Ref. 12 to the 1601 level is not solidly founded, and that, while not rigorously proved, a 1^+ assignment is considerably more plausible.

The decay properties of the $E_x = 1601$ keV level, as measured in the present and previous experiments, and as calculated under the assumption of $J^{\pi}_{\nu} = 1^+_2$, are listed in Table VI. The calculated mean life of 2300 fs is 3 times slower than the experimental results ($\tau_m = 800 \pm 150$ fs) of Ref. 19.

TABLE VIII. Decay of the $E_x = 2491$ keV level ($J^{\pi}_{\nu}, T = (2_3)^+, 1$); $\tau_m = 60 \pm 10$ fs, Ref. 19; $\tau_{\text{calc}} = 29$ fs.

Final level		Branching ratio (%)		Calculated transition strengths and widths			
J^{π}_{ν}, T	E_x (keV)	Expt. [a]	Calc.	$B(M1)$ (μ_N^2)	$\Gamma(M1) \times 10^3$ (eV)	$B(E2)$ (e^2fm^4)	$\Gamma(E2) \times 10^5$ (eV)
2^+_1, 1	0	12	22	0.029	5.2	0.1	0.8
3^+_1, 1	789		1	0.003	0.2	6.5	12.8
1^+_1, 1	1165	82	69	0.59	15.9	9.9	3.3
1^+_2, 1	1601		2	0.060	0.5	14.1	0.6
2^+_2, 1	1960	6	6	0.82	1.4	12.8	0.04

[a] Reference 12 and present work.

TABLE IX. Decay of the $E_x=2677$ keV level ($J^\pi_\nu, T=(1_3)^+, 1$); $\tau_m<10$ fs, Ref. 19; $\tau_{\mathrm{calc}}=13$ fs.

Final level		Branching ratio (%)		Calculated transition strengths and widths			
J^π_ν, T	E_x (keV)	Expt.[a]	Calc.	$B(M1)$ (μ_N^2)	$\Gamma(M1)\times10^3$ (eV)	$B(E2)$ ($e^2\,\mathrm{fm}^4$)	$\Gamma(E2)\times10^5$ (eV)
2^+_1, 1	0	100	92	0.22	49	0.1	1.1
1^+_1, 1	1165		5	0.066	2.6	4.8	3.1
1^+_2, 1	1601		1	0.047	0.7	0.2	0.02
2^+_2, 1	1960		2	0.17	0.7	4.7	0.07

[a] Reference 12 and present work.

The calculated strong branch of this state to the first $J^\pi=1^+$ state at $E_x=1165$ keV was previously undetected. While the present experiment has observed this cascade branch, it is not as strong as predicted. The implications of this disagreement are not particularly profound since an increase in the $B(M1)$ of the ground-state transition by a factor of 10 would cure the problem and still leave the matrix element classified as highly canceled.

The decay properties of the $E_x=1960$ keV $J^\pi_\nu=2^+_2$ level are listed in Table VII. The calculated mean life is somewhat too short and the observed branching strength to the $E_x=789$ keV level is not reproduced. Presumably the calculated ground-state $B(M1)$ is too large and that to the $E_x=789$ keV level too small.

The decay properties of the $E_x=2491$ keV level, listed in Table VIII, are typical and interesting. The calculations suggest that this is the third $J^\pi=2^+$ level and it is the theoretical properties of this state which are compared to the experimental results. The calculated mean life is too short by a factor of 2 compared to the results of Ref. 19. The observed distribution of decay strength to the lower states in the system is very nicely reproduced, however. The large $B(M1)$ values to the first $J^\pi=1^+$ and second $J^\pi=2^+$ levels lead to the observed dominant branch to the $E_x=1165$ keV level and to the anomalous 6% branch to the $E_x=1960$ level. The qualitative distinctiveness of this decay pattern and the match between the theory and experiment provide a rather convincing argument that the model and observed levels are correctly correlated.

The decay properties of the $E_x=2677$ keV level, assumed to be the third $J^\pi=1^+$ level, are listed in Table IX. There is reasonable agreement between theory and experiment, but the decay does not exhibit any distinctive characteristics.

The presently observed and calculated decays of the $E_x=4300$ keV $J^\pi=0^+$ $T=2$ level are listed in Table X. As would be conventionally expected, the $M1$ decays to the $J=1$ levels dominate the model spectrum, although the $B(E2)$ for the ground state

TABLE X. Decay of the $E_x=4300$ keV level ($J^\pi_\nu, T=0^+_1, 2$); $\tau_{\mathrm{calc}}\sim3$ fs.

Final level			Branching ratio (%)		Calculated transition strengths and widths			
	E_x (keV)							
J^π_ν, T	Expt.	Calc.	Expt.[a]	Calc.	$B(M1)$ (μ_N^2)	$\Gamma(M1)$ (eV)	$B(E2)$ ($e^2\,\mathrm{fm}^4$)	$\Gamma(E2)\times10^4$ (eV)
2^+_1, 1	0	0		3			5.7	68
1^+_1, 1	1165	1100	28 ± 5	29	0.16	0.057		
1^+_2, 1	1601	1640	65 ± 8	66	0.58	0.132		
2^+_2, 1	1960	1767		0			1.4	0.8
2^+_3, 1	2491	2397		0				
1^+_3, 1	2677	2792	7 ± 3	1	0.05	0.002		
1^+_4, 1	b	3361		1	0.21	0.002[c]		

[a] This work.

[b] The $J^\pi_\nu=1^+_4$ level has not been identified.

[c] This partial width was obtained with the calculated value $E_x=3361$ keV (Table V) for the $J^\pi_\nu=1^+_4$ level.

TABLE XI. Decay of the E_x=7564 keV level (J^π_ν, T=2^+_1, 2); $\tau_{\rm calc} \sim 0.3$ fs.

	Final level		Branching ratio		Calculated transition strengths and widths			
	E_x (keV)		(%)		$B(M1)$	$\Gamma(M1)$	$B(E2)$	$\Gamma(E2)\times 10^3$
J^π_ν, T	Expt.	Calc.	Expt.[a]	Calc.	(μ_N^2)	(eV)	(e^2fm^4)	(eV)
2^+_1, 1	0	0		3	0.01	0.050	0.8	16.0
3^+_1, 1	789	927		1	0.002	0.007	1.2	13.8
1^+_1, 1	1165	1100		0	0.001	0.003	0.006	0.05
1^+_2, 1	1601	1640	42 ± 6	54	0.45	1.100	0.00	0.00
2^+_2, 1	1960	1767	40 ± 6	20	0.20	0.41	0.7	3.1
2^+_3, 1	2491	2397	18 ± 4	8	0.11	0.166	1.0	2.7
1^+_3, 1	2677	2792		2	0.03	0.040	1.2	2.7
1^+_4, 1		3361		12	0.27	0.232[b]		

[a] This work.

[b] This partial width was obtained with the calculated value E_x=3361 keV (Table V).

is large enough that a more sensitive experiment might be able to confirm or reject the prediction. The preferential decay to the E_x =1601 keV level is correctly predicted by the calculation. This experimental feature, buttressed by the theoretical confirmation, is strong evidence for the $J^\pi = 1^+$, rather than $J^\pi = 2^+$, assignment to the E_x =1601 keV level. The relative strength observed to the first $J^\pi = 1^+$ level at E_x =1165 keV is also correctly reproduced by the calculation, but the 7% branch to the E_x = 2677 keV level, assumed to be the third $J^\pi = 1^+$ state, is not reproduced. The calculation yields a large $B(M1)$ for the transition to the fourth $J^\pi = 1^+$ state but the energy difference is so small that this branch is below the level of sensitivity of the present data.

The decay of the E_x = 7564 keV $J^\pi = 2^+$ T = 2 level presents a larger selection of possible conventional decays, since the $M1$ operator can connect this state to $J^\pi = 1^+$, 2^+, and 3^+ final states. The present experimental and theoretical results are presented in Table XI. The model results correctly produce the inhibition of decay to the first $J^\pi = 2^+$, 3^+, and 1^+ states. The calculation further distributes a qualitatively correct apportionment of strength among the E_x =1601 keV ($J^\pi_\nu = 1^+_2$), 1960 keV (2^+_2), and 2491 keV (2^+_3) states. As in the case of the $J^\pi = 0^+$ T = 2 state, the model yields a large $B(M1)$ for the transition to the fourth $J^\pi = 1^+$ state. In this instance, the $B(M1)$ yields a branch that should be visible, and the nonobservance of such a decay in the present experiment indicates that the model connection here is too large.

To summarize, the present experimental knowledge of the electromagnetic decays of the levels of ^{36}Cl is now reasonably extensive. Insofar as positive-parity levels are concerned, the observed phenomena are reproduced by mixed configuration shell-model calculations with rather good accuracy, both with respect to absolute strengths where such are available and to branching ratios where lifetimes have not been or cannot be measured. The $M1$ decay mode dominates almost all calculated decays so relatively little information is gained about $E2$ properties. The over-all agreement between experiment and theory is such that no imperative need for renormalization of the bare-nucleon coefficients of the $M1$ operator is evident. On the basis of the present results, the extension of the study to the $T_z = 0$ system can rely upon the guidance of calculated decay schemes with some confidence.

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