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Electromagnetic Transition Rates in ^{38}Cl and ^{40}K

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The attenuated-Doppler-shift method was used to measure the mean lives of low-lying states in ^{38}Cl and ^{40}K. States were populated by the (d,p) reaction and the recoil direction was defined by coincidence with the outgoing proton. While the positions of the levels in these two nuclei give encouragement to the belief that many of the states are well described as members of simple particle-hole or particle-particle multiplets, it is immediately apparent that the magnetic dipole transition rates do not fit the simple picture even if effective moments are used. A recent theoretical study has shown that some admixtures that can be expected will significantly alter the $M1$ rates, but the present results are not in good agreement with the theoretical predictions. Other available lifetime data on these nuclei support the present contention that there are severe discrepancies between the observed rates and those predicted by the best available shell-model calculations.

INTRODUCTION

The nuclei ^{38}Cl and ^{40}K provide an interesting testing ground for the shell model. In the simple shell-model picture in which ^{40}Ca is a doubly-closed-shell nucleus, ^{38}Cl is described by the configuration $(\pi d_{3/2})(\nu f_{7/2})$, and ^{40}K by the configuration $(\pi d_{3/2})^{-1}(\nu f_{7/2})$, each configuration producing a quartet of states. At a low excitation in each nucleus, the shell model predicts another quartet of negative-parity states of the $(\pi d_{3/2})^{\pm 1}(\nu p_{3/2})$ configuration. Since this model is successful in predicting many of the gross features of the low-lying ^{38}Cl and ^{40}K levels, it is worthwhile to start applying the more stringent test of comparing electromagnetic transition rates with the theoretical predictions.

Our measurements of the $M1$ rates of transitions among members of the ground-state quartet in each nucleus were not in agreement with the simple picture.[1] The present report on the measurement of the lifetimes of a number of higher states completes our study of these two nuclides. In the interim, transition rates in ^{38}Cl and ^{40}K have been reported by several other groups: Wechsung *et al.*[2] reported on transitions in ^{40}K that proceed from levels up to 2.626-MeV excitation energy, James *et al.*[3] measured the lifetimes of ^{40}K levels up to 3.153-MeV excitation energy, and Engelbertink and Olness[4] studied the levels of ^{38}Cl up to an excitation energy of 2.743 MeV.

The ^{39}K$(d,p)^{40}$K reaction has been studied by Enge, Irwin, and Weaner[5] and more recently by Fink.[6] A study of the ^{37}Cl$(d;p)^{38}$Cl reaction has been reported by Rapaport and Buechner.[7] Early theoretical work[8,9] showed that the energy of the lowest four levels in one of these nuclei could be accurately predicted from the position of the lowest four levels in the other if the simple shell-model configurations given above were assumed. In their recent theoretical investigation of the magnetic multipole properties of the low-lying states of these two nuclei, Kurath and Lawson[10] made extensive use of the present lifetime measurements on 17 levels in ^{40}K (up to 3.629 MeV excitation) and eight levels in ^{38}Cl (up to 2.743 MeV excitation).

The following sections describe the measurements and the results and conclude by comparing the results from the several experimental groups with each other and with theory.

EXPERIMENTAL METHOD

The attenuated-Doppler-shift method was used for the lifetime measurements; the experimental layout was the same as that used for earlier measurements.[1,11] States were populated with the ^{37}Cl$(d, p)^{38}$Cl and ^{39}K$(d, p)^{40}$K reactions induced by 3.5-MeV deuterons from the Argonne Dynamitron accelerator. Data on ^{40}K were taken with thick and thin targets consisting respectively of 1300 μg/cm^2 of ^{39}KI on a 1500-μg/cm^2 gold backing and of 30 μg/cm^2 of ^{39}KI on a 1000-μg/cm^2 gold backing. The range of the ^{40}K recoils in KI was approximately 400 μg/cm^2. The thick targets for the ^{38}Cl data were 1700 μg/cm^2 and 1000 μg/cm^2 of PbCl$_2$, (enriched in ^{37}Cl) on 1500 μg/cm^2 gold and the thin one was 50 μg/cm^2 of PbCl$_2$ on an 800-μg/cm^2 gold backing. The range of the ^{38}Cl recoils in PbCl$_2$ was approximately 360 μg/cm^2.

The nominal target thicknesses determined from the geometry of the evaporator were checked by measuring the energy lost by 5-MeV α particles. The two values were found to agree to within about 30%. It should be noted that since most of the recoils in a thick target would come to rest in the target material, the observed shift would be nearly independent of the actual target thickness. At the other extreme, the thin targets would absorb only a small fraction of the recoil energy and therefore the shift would not be a significantly dependent on the target thickness unless the state were very short lived.

The energy resolution of the Ge(Li) detector was typically 5 keV full width at half maximum (FWHM) under experimental conditions.

The recoil direction of the residual nucleus was determined by coincidence between the γ ray and the outgoing proton. Two proton detectors were used simultaneously: One was positioned at 0° and therefore detected protons in coincidence with low-energy recoil nuclei, while the other was positioned in a backward quadrant so that it detected protons in coincidence with residual nuclei moving almost along the axis of the Ge(Li) detector with an energy of a few hundred keV. For most of the work the backward proton detector was at 132° and the Ge(Li) detector at 157°. The exception was the ^{38}Cl run with the 1000-μg/cm^2 target, for which the proton detector was at 71° and the γ-ray detector at 112°. The advantages of this double-coincidence method have been enumerated elsewhere.[12]

Detector pulses were processed with conventional electronics, and the coincidence events were digitized and recorded event by event on magnetic tape. The γ rays were digitized in 4096 channels, and the protons from each of the two silicon surface-barrier detectors, were digitized in 512 channels. Although some of the γ-ray spectra could be monitored on line, most were obtained by processing the data tapes off line on an IBM-360/75 computer. The data were sorted into two 4096 $\times$ 512-channel matrices on a disk pack, and a model No. 2250 graphic display terminal was then used to strip out the spectra, perform background subtractions, and determine peak centroids.[13]

Lifetimes were extracted from the measured energy shifts by using the slowing-down theory of Lindhard, Scharff, and Schiøtt[14] modified to include the scattering correction given by Blaugrund.[15] In computing $F \equiv \Delta E_{\rm obs}/\Delta E_{\rm full}$ for each state, the factors $f_e = 1.16$ and $f_n = 1.0$ were used as multipliers for the electronic and nuclear stopping powers, respectively. The target was considered to be made up of a number of equal layers (3 for the thin targets and about 20 for the thick targets), and the shift as a function of mean life was calculated for γ rays in coincidence with both proton detectors under the assumption that the reaction took place at the center of each layer. The results for all of the layers were then averaged. A small correction of about 1% was made in order to correct for the fact that the finite solid angle subtended by the Ge(Li) detector led to the observed shift being slightly less than the shift for a point detector.

EXPERIMENTAL RESULTS

A. ^{40}K

Shifted and unshifted lines from one of the ^{40}K states are shown in Fig. 1. Table I lists the observed shifts and the mean lives that were extracted therefrom. The γ decays of all but four of the states below 2.80 MeV were observed, the exceptions being the 30-keV first excited state, the 1.644-MeV state (which is too long-lived[16] to have triggered a significant number of coincidences), and the 2.397- and 2.542-MeV states (which were probably too weakly populated). Three states above 2.80 MeV were also studied.

For all of the observed states below 2.60 MeV, the F values were found to be distinct from both 0 and 1 and the γ-ray peaks in coincidence with the backward-angle proton detector were observed to be Doppler broadened. The 2.261-MeV state was the only one for which the two determinations did not agree within the experimental error. However, the discrepancy here was less than 2 standard deviations: The thin-target F predicted from the thick-target mean life was 73%, while the observed value was $25 \pm 27\%$.

For the 2.731-, 2.787-, 3.110-, and 3.629-MeV states, the measured F values did not differ significantly from unity and therefore only upper limits could be placed on the lifetimes of these states. Although poor statistics prevented the evaluation of Doppler broadening in the transitions from the 3.228-MeV state, all five measured transitions showed some degree of attenuation of the shift; the smallest shifts were measured with the targets in which the recoil ^{40}K nuclei were stopped in gold.

The lifetimes resulting from the present measurements are also compared with those of Refs. 2 and 3. For these Table I gives only the statistical uncertainties, with no allowance for any uncertainty in the slowing down times. In comparing the results from the different groups, the inclusion of possible errors in the slowing-down times could mask real experimental discrepancies since all of the groups used the same slowing-down theory with nearly the same parameters and had recoils moving at approximately the same velocities. Furthermore, the main interest is in relative transition rates. It should be remembered, however, that the absolute transition rates con-

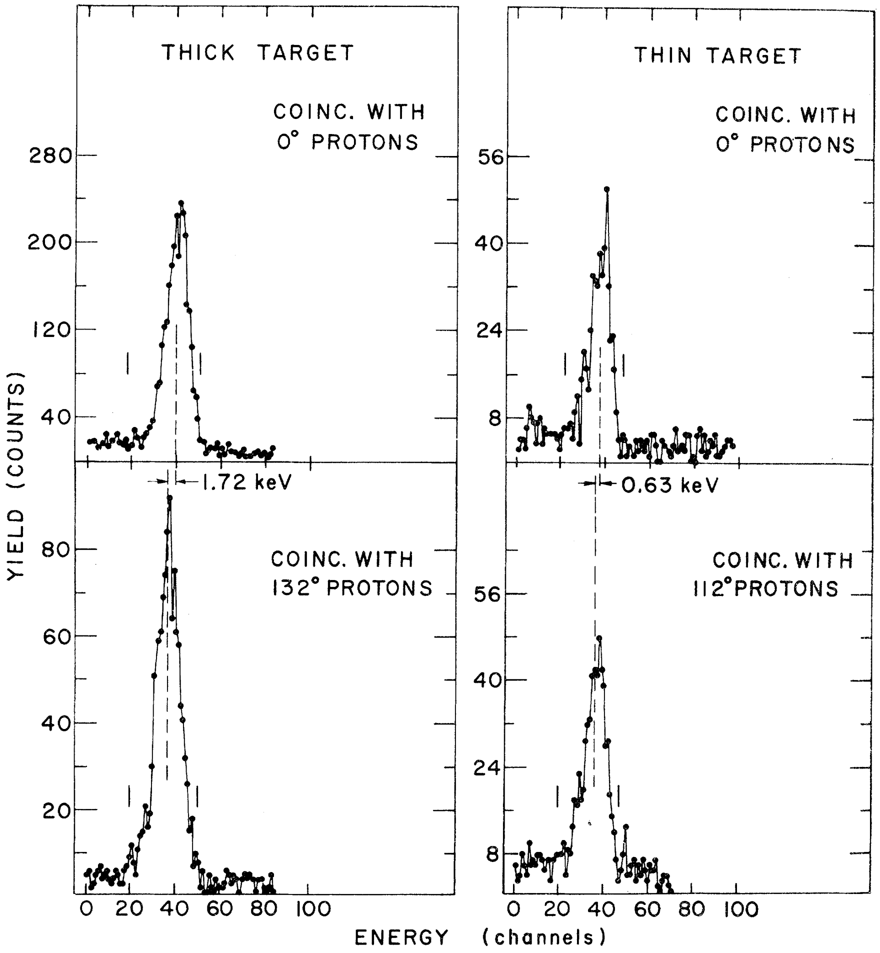

FIG. 1. γ-ray spectra showing shifted and unshifted peaks for the 770-keV transition in coincidence with protons from the $^{39}\mathrm{K}(d,p)$ reaction to the 0.800-MeV state in ^{40}K. The thick target was 1.3-mg/cm^2 KI on gold; the thin target was 30-μg/cm^2 KI on gold. The γ-ray detector was at 157° and the average recoil direction was −23°, where the negative sign indicates that the recoils were moving away from the detector.

tain an additional error of about ±25% due to an imperfect knowledge of the slowing-down curve.

Since the present work employed coincidences while the other studies involved only singles measurements, the statistical errors in the present work were somewhat greater. We believe that this defect in the coincidence method is more than compensated for by a greater freedom from systematic errors, but this advantage is not apparent, of course, when only statistical errors are given. The three sets of results show good agreement. There does not appear to be any systematic difference between the present work and the other results and there is no better over-all agreement with one group than with the other.

γ-ray branching ratios in ^{40}K have been measured a number of times[2,3,17,18] and the results are in good agreement. Occasionally one group or another missed a weak branch. An average of these branching-ratio determinations[2,3,17,18] was used in determining individual transition strengths. Relative intensities observed in the present work appeared to be consistent with the quoted branching ratios. Multipole mixing ratios for the γ-ray decays of low-lying ^{40}K states have been measured twice[2,17] with consistent results, and again the reported ratios were averaged in determining the rate of the multipole components.

Table II summarizes the reduced transition probabilities determined from the "adopted best" lifetime values of Table I. The quantity tabulated is the measured transition probability in single-particle units (Weisskopf units) defined as

$$T_{\mathrm{sp}}(E1) = 1.04\times 10^{14} A^{2/3} E_\gamma{}^3\ \mathrm{sec}^{-1},$$

$$T_{\mathrm{sp}}(E2) = 7.38\times 10^{7} A^{4/3} E_\gamma{}^5\ \mathrm{sec}^{-1},$$

$$T_{\mathrm{sp}}(M1) = 3.11\times 10^{13} E_\gamma{}^3\ \mathrm{sec}^{-1},$$

$$T_{\mathrm{sp}}(M2) = 2.21\times 10^{7} A^{2/3} E_\gamma{}^5\ \mathrm{sec}^{-1},$$

TABLE I. Observed shifts and mean lives of low-lying states in ^{40}K. All known levels below 2.80 MeV are listed. Above this energy, only those levels observed in the present work are listed.

$E_i \rightarrow E_f$	1.3 mg/cm^2 ^{39}KI on gold		30 μg/cm^2 ^{39}KI on gold		Adopted present work	Ref. 2	Ref. 3	Adopted best value
(keV) (keV)	F (%)	τ (fsec)	F (%)	τ (fsec)	τ (fsec)	τ (fsec)	τ (fsec)	τ (fsec)
30 → 0								$(6.0\pm0.4)\times10^6$ [a]
800 → 30	39 ± 3	580 ± 70	16 ± 7	530^{+400}_{-200}	580 ± 70	500 ± 70	370 ± 30	480 ± 50
891 → 0	19 ± 2	1550 ± 250	≤ 5	≥ 1450	1550 ± 250	1500 ± 200	1000 ± 80	1400 ± 150
1644								$(4.9\pm0.1)\times10^8$ [b]
1959 → 800	30 ± 9	830^{+450}_{-250}	33 ± 24	220^{+760}_{-120}	600^{+400}_{-200}	1100 ± 150	940 ± 110	940 ± 100
2047 → 30	47 ± 5	440 ± 100	36 ± 14	200^{+150}_{-80}				
→ 800	41 ± 4	530 ± 90	15 ± 5	550^{+250}_{-150}	450 ± 70	560 ± 30	500 ± 100	500 ± 50
2070 → 800	40 ± 19	550^{+750}_{-280}	29 ± 38	$260^{+\infty}_{-190}$				
→ 891	54 ± 15	330^{+240}_{-140}			380^{+200}_{-130}	700 ± 140	590 ± 100	570 ± 100
2103 → 800	42 ± 6	520 ± 100	15 ± 11	560^{+2300}_{-300}	520 ± 100	1000 ± 150	650 ± 120	700 ± 100
2261 → 0	113 ± 32	≤ 110						
→ 30	89 ± 8	55^{+55}_{-30}	25 ± 27	$300^{+\infty}_{-190}$	70^{+80}_{-40}	80 ± 20	88 ± 12	80 ± 15
2290 → 1644	54 ± 20	330^{+350}_{-180}			330^{+350}_{-180}	110 ± 30	114 ± 18	140 ± 20
2291 → 0	56 ± 12	310^{+180}_{-120}			310^{+180}_{-120}	250 ± 50	207 ± 15	250 ± 40
2397						50 ± 20	≤ 60	50 ± 20
2419 → 30	59 ± 27	270^{+460}_{-190}						
→ 800	34 ± 17	670^{+1080}_{-300}			400^{+400}_{-150}	>1000	660^{+400}_{-200}	500^{+300}_{-150}
2542							>3000	>3000
2575 → 30	67 ± 12	200^{+120}_{-60}	27 ± 24	280^{+3000}_{-180}	200^{+120}_{-50}	100 ± 30	220 ± 70	180 ± 50
2626 → 800	86 ± 29	75^{+225}_{-75}	22 ± 34	$360^{+\infty}_{-280}$				
→ 2103	41 ± 14	530^{+370}_{-210}			320^{+200}_{-120}	370 ± 40	240 ± 80	310 ± 40
2731 → 1644	105 ± 26	<120			<120		<55	<55
2787 → 1959	77 ± 57	<1000			<1000		80 ± 30	80 ± 30
3110 → 1644	96 ± 10	20^{+120}_{-20}	67 ± 43	<320	<140			<140
3228 → 0	97 ± 24	20^{+135}_{-22}	76 ± 33	50^{+100}_{-50}				
→ 30	92 ± 12	42^{+70}_{-42}	84 ± 26	30^{+60}_{-30}				
→ 800	82 ± 31	105^{+260}_{-105}			40 ± 30			40 ± 30
3629 → 0	96 ± 16	20^{+105}_{-20}						
→ 2070	74 ± 31	150^{+340}_{-150}						
→ 2397	100 ± 19	<110			<100			<100

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[b] Reference 16.

TABLE II. Electromagnetic transition strengths (single-particle units) in ^{40}K. Strengths were calculated by use of the "adopted best values" of Table I for the mean lives, an average of the results of Refs. 2, 3, 17, and 18 for the branching ratios, and an average of Refs. 2 and 17 for the mixing ratios. Where the parity of a transition is in doubt, rates for both possibilities are listed.

$(J^\pi)_i$	$E_i \to E_f$ (keV) (keV)	Branching ratio (%)	Multipole mixing ratio δ	Transition strengths (single-particle units)				
				$E1$	$M1$	$E2$	$M2$	$E3$
3^-	30 → 0	100	Pure $M1$		0.16			
2^-	800 → 30	100	0.00 ± 0.01		0.15	<0.076		
5^-	891 → 0	100	-0.11 ± 0.05		0.033	1.5		
0^+	1644 → 30	80	Pure $E3$					0.96
	→ 800	20	Pure $E2$				0.031	
2^+	1959 → 30	20	-0.10 ± 0.04	2.5×10^{-5}			0.31	
	→ 800	80	0.00 ± 0.02	4.8×10^{-4}			<0.63	
2^-	2047 → 0	29	Pure $E2$			1.6		
	→ 30	31	-0.03 ± 0.03		2.4×10^{-3}	$<6.6\times10^{-3}$		
			9.0 ± 2.0		2.9×10^{-5}	1.8		
	→ 800	40	-0.12 ± 0.09		0.013	0.37		
3^-	2070 → 0	34	0.07 ± 0.05		3.1×10^{-3}	7.7×10^{-3}		
	→ 30	54	0.26 ± 0.10		3.4×10^{-3}	0.17		
	→ 800	6	0.15 ± 0.10		1.7×10^{-3}	0.059		
	→ 891	6	Pure $E2$			4.6		
1^-	2103 → 30	70	Pure $E2$			2.5		
	→ 800	30	-0.30 ± 0.06		5.7×10^{-3}	0.93		
3^+	2261 → 0	20	0.02 ± 0.05	1.9×10^{-4}			<0.77	
	→ 30	80	-0.02 ± 0.05	7.8×10^{-4}			<0.29	
1^+	2290 → 800	35	-0.15 ± 0.15	6.6×10^{-4}			<29	
	→ 1644	55	Pure $M1$		0.47			
	→ 1959	10			0.63			
$4(3)^-$	2291 → 0	88	-0.10 ± 0.25 [a]		0.009	$<5.4\times10^{-2}$		
			1.0 ± 0.3 [b]		4.7×10^{-3}	2.7		
	→ 891	12			5.7×10^{-3}			
$3(2)^-$	2397 → 0	31			0.015 [b]	≤ 7.8 [b] 7.8 [c]		
	→ 30	69			0.034			
$(2,3)^-$	2419 → 0	7			$<3.2\times10^{-4}$	<0.17		
	→ 30	17			$<7.3\times10^{-4}$	<0.43		
	→ 800	73	-0.05 ± 0.10 [c]		0.011	<0.30		
			-2.0 ± 0.6 [c]		2.2×10^{-3}	10.3		
			-0.35 ± 0.05 [b]		0.010	1.4		
	→ 1959	3			0.02			
$(2,4)^+$	2575 → 30	100	-0.08 ± 0.03 [c]	$<2.9\times10^{-4}$			<1.3	
			-0.06 ± 0.02 [a]	$<2.9\times10^{-4}$			<0.76	
0^-	2626 → 800	30	Pure $E2$			4.7		
	→ 2103	70	Pure $M1$		0.51			
$1^{(+)}$	2731 → 1644	100		>0.012	>0.45			
3^-	2787 → 0	23			$<4.3\times10^{-3}$	<1.6		
	→ 30	27			$<5.1\times10^{-3}$	<2.1		
	→ 891	12				6.0		
	→ 1959	19		3.6×10^{-3}				
	→ 2291	19			0.63			
1^+	3110 → 1644	50			>0.036			
	→ 1959	50			>0.076			
$(2,3)^-$	3228 → 0	25			$<6.0\times10^{-3}$	<1.8		
	→ 30	55			$<1.3\times10^{-2}$	<4.1		
	→ 800	20			$<1.1\times10^{-2}$	<5.9		
$(2,3)^-$	3629 → 0	45			$>3.0\times10^{-3}$ [d]	>0.71 [e]		
	→ 30	20			$>1.4\times10^{-3}$ [d]	>0.33 [e]		
	→ 2070	10			$>8.5\times10^{-3}$			
	→ 2397	25			>0.043			

[a] If $J = 4$.

[b] If $J = 3$.

[c] If $J = 2$.

[d] If the transition were pure $M1$.

[e] If the transition were pure $E2$.

where E_γ is the transition energy in MeV.

The measured transition strengths (Table II) are consistent with the spins and parities that have been assigned previously[2,3,17] in ^{40}K. In addition, they furnish the following information. The 2.291-MeV state has been assigned[17] $J=4(3)$. The transition strengths for the 2.291 → 0.891-MeV branch indicate that if $J=3$, then π is odd. Recent (d,p) data[6] require both an even- and an odd-parity level in this region, and the 2.290-MeV state has been assigned[18] positive parity. Thus a 3^- or 4^- assignment gives the best fit to all of the data. James *et al.*[3] assigned $J=1$ to the 2.731-MeV state on the basis of transition strengths; the speed of the transition to the 0^+ state at 1.644 MeV is at least an order of magnitude too great for it to be a quadrupole transition. Positive parity appears to be favored, since if the 2.731 → 1.644-MeV transition were $E1$ its strength would be $>10^{-2}$ Weisskopf units (W.u.), which would be unusually large for this mass region.[19] The finding[5,6] of $l_n=1$ for the 2.397-MeV state combined with the strength of the ground-state transition leaves only 2^- and 3^- as possibilities, with 2^- requiring what for this nucleus is a rather fast $E2$ transition to ground.

Spins have not been previously assigned to the states at 3.110, 3.228, and 3.629 MeV. The speed of the transition from the 3.110-MeV state to the 0^+ state at 1.644-MeV limits the former to $1^\pm$. Since the earlier[5] (d,p) data indicated $l_n=0$, the likely assignment remains 1^+. For both the 3.228- and the 3.629-MeV states the combination of neutron momentum[5,6] $l_n=1$ and the speed of the transition to the 4^- ground state leaves 2^- and 3^- as the only possible assignments.

B. ^{38}Cl

Decays were observed from all but three of the known states below 2.75 MeV, the exceptions being the long-lived 0.671-MeV state and the states at 1.942 and 2.455 MeV. Mean lives were determined for all of the states that were studied, and for most states the runs with the three different targets gave consistent results (Table III). The exceptions were the 1.981-MeV state (for which the mean life from the thin-target run was longer than those from the other runs) and the 2.743-MeV state (for which the mean life obtained with the 1-mg/cm^2 target was shorter than the other two), but in neither case was the deviant mean life more than 2 standard deviations away from the other two. While the relative mean lives agree well with those of Ref. 4, the present lifetimes are on the average smaller by about a factor of 1.7. The discrepancy lies in the measurements themselves, rather than in the stopping-power codes. When the F values reported in Ref. 4 are put through our code, the resulting lifetimes are virtually those of Ref. 4. Similarly, when the present experimental results were analyzed with the Brookhaven program, the resulting mean lives were virtually identical to those reported here. Since the present ^{40}K results were in good agreement with those of other groups (Table I), it seems unlikely that there is an unsuspected systematic error in the present experiment. On the other

TABLE III. Mean lives of low-lying excited states in ^{38}Cl.

$E_i \to E_f$	1.7 mg/cm^2 PbCl$_2$ on gold		1.0 mg/cm^2 PbCl$_2$ on gold		50 μg/cm^2 PbCl$_2$ on gold		Mean life τ of initial state		
(keV) (keV)	F (%)	τ (fsec)	F (%)	τ (fsec)	F (%)	τ (fsec)	Adopted (fsec)	Ref. 4 (fsec)	Ref. 20 (fsec)
671							1.07 ± 0.05 sec [a]		
755 → 0	31 ± 3	340 ± 50	50 ± 4	260 ± 40	29 ± 3	260 ± 40	290 ± 30	530 ± 180	
1309 → 671	16 ± 7	760^{+680}_{-260}	32 ± 8	490^{+180}_{-120}	20 ± 7	410^{+200}_{-150}			
→ 755	3 ± 25	>400					560^{+150}_{-100}	1000^{+900}_{-400}	
1617 → 0	8 ± 5	1600^{+2900}_{-700}	12 ± 7	1500^{+2500}_{-600}	≤10	≥900			
→ 755	10 ± 7	1230^{+3300}_{-510}			11 ± 10	850^{+6000}_{-460}	1500^{+1000}_{-500}	2300^{+2300}_{-900}	2200 ± 200
1692 → 0	10 ± 2	1250^{+350}_{-250}	21 ± 4	870 ± 210	5 ± 3	1900^{+3500}_{-800}	1200^{+300}_{-200}	1900 ± 700	
1746 → 0	18 ± 4	650^{+250}_{-160}	18 ± 4	1000 ± 250	2 ± 4	$4800^{+\infty}_{-3200}$	1000 ± 300	2100^{+1400}_{-700}	
1785 → 755	90 ± 28	20^{+80}_{-20}			41 ± 36	160^{+1700}_{-120}	90 ± 60	90 ± 30	
1942									
1981 → 0	35 ± 3	280 ± 40	59 ± 4	180 ± 40	<9	>950			
→ 755	40 ± 5	230 ± 50	55 ± 8	200 ± 50	10 ± 6	900^{+1400}_{-360}	260 ± 80	430 ± 90	560 ± 80
2743 → 1309	70 ± 8	70^{+35}_{-25}	115 ± 15		50 ± 24	120^{+190}_{-70}			
→ 1617	91 ± 16	20^{+40}_{-20}			75 ± 29	50^{+90}_{-50}			
→ 1785	90 ± 9	23^{+17}_{-23}	123 ± 15		94 ± 16	15^{+25}_{-15}	40 ± 20	≤30	

[a] P. M. Endt and C. van der Leun, Nucl. Phys. A105, 1 (1967).

hand, when the Brookhaven group remeasured the mean lives of the 1.617- and 1.981-MeV states in an experiment performed with a heavy-ion beam,[20] the values found agreed better with Ref. 4 than with the present results. It is hoped that other groups will make measurements on ^{38}Cl in order to resolve this discrepancy. In the meantime, it should be emphasized that the major conclusions of the present work – in particular, the various discrepancies between theory and experiment – are based mainly on the relative values of the mean lives rather than on absolute values. In the analysis that follows, the present results have been used.

γ-ray branching ratios have been measured[4] in ^{38}Cl and are used in deriving individual transition strengths (Table IV); multipole mixing ratios have not been reported.

Spins and parities have been recently assigned on the basis of the available γ-ray and nucleon-transfer data.[4] The present work is consistent with these assignments.

DISCUSSION

Most of the recent discussion of these two nuclei has been concentrated on classifying energy levels as members of various particle-hole and particle-particle multiplets. While such an approach has enjoyed considerable success in relating the levels of the two nuclei through the use of the Pandya transformation[4,8,9] the fact that the $M1$ transition rates among the lowest four states are not correctly predicted[1] in either nucleus demonstrates that the simple picture needs modification. Kurath and Lawson[10] investigated the effects of small particle-hole admixtures and showed that while the individual transition rates among these lowest states could be altered radically, only marginally better agreement with experiment was achieved in ^{40}K and the already poor agreement in ^{38}Cl was actually worsened.

It is very unlikely that the discrepancy between theory and experiment for the ground-state quartets is due to experimental error. In ^{40}K three different groups have obtained virtually the same results. It is mainly the relative lifetimes that matter[1,10] in ^{38}Cl, and the relative lifetimes from the present work are in good agreement with Ref. 4. Furthermore, in the present work the ratio of the intensity of the 1.309 → 0.671-MeV branch to that of the 1.309 → 0.755-MeV branch in ^{38}Cl was found to be 3.6 ± 0.5, while Engelbertink and Olness[4] found this ratio to be 4.1 ± 0.6. In contrast,

TABLE IV. Electromagnetic transition strengths in ^{38}Cl. The mean lives found in the present work were used for all except the 671-keV state. For any mixed dipole-quadrupole transition for which the pure quadrupole rate would be greater than 30 W.u., the dipole rate was computed under the assumption that the quadrupole contribution could be neglected.

$E_i \rightarrow E_f$ (keV) (keV)	$(J^\pi)_i$	Branching ratio[a] (%)	Transition strength (single-particle units)				
			$E1$	$M1$	$E2$	$M2$	$M3$
671 → 0	5^-	100					0.011
755 → 0	3^-	100		0.26	≤ 1490		
1309 → 0	4^-	8			4.0		
→ 671		74		0.16	≤ 1400		
→ 755		18		5.6×10^{-2}	≤ 650		
1617 → 0	3^-	21		$\leq 1.1 \times 10^{-3}$	≤ 1.3		
→ 671		3			2.8		
→ 755		25		8.4×10^{-3}	≤ 37		
→ 1309		51		0.37	$\leq 1.3 \times 10^4$		
1692 → 0	$(1)^-$	92		$\leq 5.1 \times 10^{-3}$	≤ 5.8		
→ 755		8			9.8		
1746 → 0	0^-	100			6.5		
1785 → 755	$(2,3,4)^+$	100	8.9×10^{-3}			$\leq 3.2 \times 10^4$	
1981 → 0	2^-	32		$\leq 4.9 \times 10^{-3}$	≤ 4.1		
→ 755		25		1.6×10^{-2}	≤ 44		
→ 1617		31		0.78	$\leq 1.9 \times 10^4$		
→ 1692		12		0.60	$\leq 2.3 \times 10^4$		
2743 → 0	3^-	25		$\leq 8.9 \times 10^{-3}$	≤ 4.0		
→ 755		6		$\leq 4.9 \times 10^{-3}$	≤ 4.9		
→ 1309		33		8.6×10^{-2}	≤ 140		
→ 1617		12		6.5×10^{-2}	≤ 170		
→ 1785		24	5.8×10^{-3}			$\leq 2.9 \times 10^4$	

[a] Reference 4.

the value for a pure $(\pi d_{3/2})(\nu f_{7/2})$ multiplet[1] would be 1.18 and Kurath and Lawson[10] predict a value of 0.95.

A quartet of states in each of the nuclei has been designated as being of the $(\pi d_{3/2})(\nu p_{3/2})$ configuration. In ^{40}K, when the (d,p) results,[5,6] the lifetimes, and the angular-correlation data[2,17] are considered, the assignments 2^-, 3^-, 1^-, and 0^- for the 2.047-, 2.070-, 2.103-, and 2.626-MeV states, respectively, can be made with a satisfactory degree of certainty, although it must be noted that the assignments for both the 2.047- and 2.626-MeV states are to some degree based on conjecture. The $(d_{3/2})^{-1}(p_{3/2})$ multiplet appears to be considerably fragmented, since each proton group feeding these states shows substantially less than the total $p_{3/2}$ strength for the spin involved. In contrast, nearly all of the $f_{7/2}$ strengths are accounted for in the protons feeding the ground-state quartet.

Combining the (d,p) data,[7] the γ-ray data, and the levels predicted by the Pandya transformation of the $(\pi d_{3/2})^{-1}(\nu p_{3/2})$ quartet in ^{40}K leads to the identification of the $(\pi d_{3/2})(\nu p_{3/2})$ quartet in ^{38}Cl: The states at 1.617, 1.692, 1.746, and 1.981 MeV, are respectively, the 3^-, 1^-, 0^-, and 2^- members. If one takes the quoted spectroscopic factors[6,7] literally, it appears that in ^{38}Cl there is more fragmenting of the $f_{7/2}$ strength but less fragmenting of the $p_{3/2}$ strength.

TABLE V. Speeds (single-particle units) of intramultiplet (allowed) and intermultiplet (forbidden) $M1$ transitions between states of the two lowest odd-parity multiplets in ^{40}K and ^{38}Cl. In order to make comparisons more valid, wherever possible the speeds are obtained from the mean lives measured in the present work. A blank signifies that the intensity of the transition is so small that the branch has not been observed.

Configuration	Spins	^{40}K	^{38}Cl
	Allowed		
$(\pi d_{3/2})(\nu f_{7/2})$	$2 \longleftrightarrow 3$	0.12	0.26
	$3 \longleftrightarrow 4$	0.15	0.064
	$4 \longleftrightarrow 5$	0.029	0.17
$(\pi d_{3/2})(\nu p_{3/2})$	$0 \longleftrightarrow 1$	0.49	
	$1 \longleftrightarrow 2$		0.60
	$2 \longleftrightarrow 3$		0.77
	Forbidden		
$(\pi d_{3/2})(\nu p_{3/2})$ $\longleftrightarrow (\pi d_{3/2})(\nu f_{7/2})$	$1 \rightarrow 2$	0.0084	≤ 0.0051
	$2 \rightarrow 2$	0.015	≤ 0.0055
	$2 \rightarrow 3$	0.0023[a]	0.018
	$3 \rightarrow 2$	0.0025	≤ 0.0010
	$3 \rightarrow 3$	0.0054	0.009
	$3 \rightarrow 4$	0.0033	0.37

[a] The other solution for δ (Ref. 2) gives 3.2×10^{-5}.

It can be concluded from the work of Kurath and Lawson[10] that simple shell-model calculations of the small admixtures in the lower multiplets plus the mixing between the multiplets is unlikely to lead to an adequate reproduction of the experimental intramultiplet transition rates. The intermultiplet transition rates can also be considered. If the configurations were pure, then $M1$ transitions between members of the lowest two multiplets $[(\pi d_{3/2})(\nu f_{7/2})$ and $(\pi d_{3/2})(\nu p_{3/2})]$ would be forbidden, since such γ rays would have to carry off two units of orbital angular momentum. In Table V, which compares the speeds of the forbidden with those of the allowed transitions, it can be seen that while most of the transition rates fit into the expected pattern there is one glaring exception: The $1.617 \rightarrow 1.309$-MeV transition in ^{38}Cl should be forbidden, yet it has nearly the single-particle speed and is about as fast as the average allowed transition. Including small admixtures of other configurations does not appear to help, since Kurath and Lawson[10] predict the speed of this transition to be 1/600 of the single-particle value.

The gross discrepancy between theory and experiment in the speed of the $1.617 \rightarrow 1.309$-MeV transition in ^{38}Cl has led us to make a special effort to verify this transition rate. The quoted speed is derived from two experimentally determined quantities: the lifetime of the 1.617-MeV state and the branching ratio for the 308-keV branch. The crux of the lifetime determination is to establish that some significant Doppler shift is present when the recoils are brought to rest in a $PbCl_2$ target. In the present work, three independent measurements all showed about a 10% shift and the shift in the composite result was about $2\frac{1}{2}$ standard deviations away from no shift. Furthermore, as can be seen in Fig. 2, the 1.617-MeV peak in coincidence with the backward proton detector showed a distinct broadening on the low-energy side, as expected if the state does not live too long. This broadening was in addition to the very small amount of low-energy "tailing" that was present in the higher-energy peaks due to radiation damage. Under similar circumstances, Engelbertink and Olness[4] also observed a shift of about 10%, which differed from zero shift by 2 standard deviations. Furthermore, the recent work of Warburton *et al.*[20] yields a mean life of about 2.2×10^{-12} sec for the state. Thus, the good agreement among various determinations renders it rather unlikely that the quoted lifetime of the 1.617-MeV state is greatly in error.

In the present work the biases were set such that a 308-keV γ ray would not have been observed. However, the intensity of this branch could be measured by observing the protons feed-

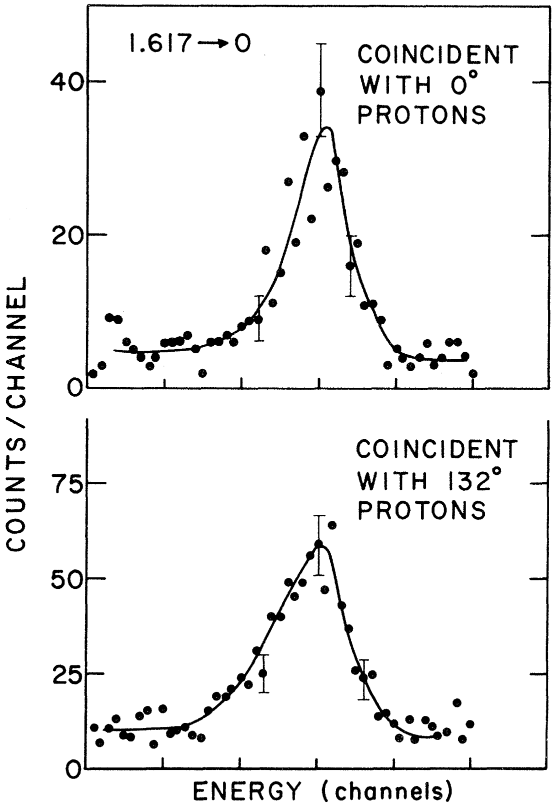

FIG. 2. γ-ray spectra showing the peaks for the 1.617-MeV transition in coincidence with protons from the ^{37}Cl(d,p) reaction to the 1.616-MeV state in ^{38}Cl. The positions of the detectors were the same as in Fig. 1.

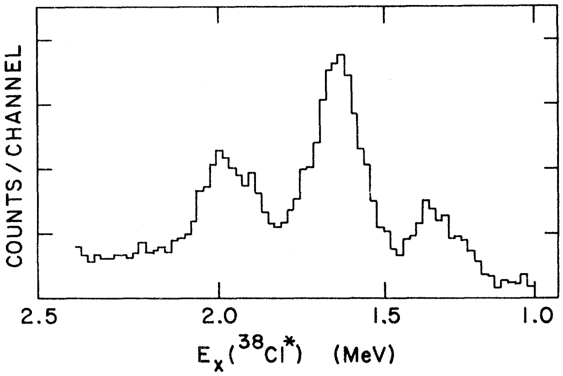

FIG. 3. Proton spectrum in coincidence with the 638-keV γ-ray peak. The 638-keV transition is the main branch from the 1.309-MeV state in ^{38}Cl. Proton groups are seen feeding the 1.309-, 1.617-, and 1.981-MeV states.

ing the 1.617-MeV state in coincidence with a 638-keV γ ray from the 1.309-MeV state (Fig. 3). Since each coincident event was recorded in digitized form on magnetic tape, it was possible to establish this cascade by searching tapes after the data taking was complete. From the proton spectrum in coincidence with the 638-keV γ ray, it could be concluded that a state at 1.62 ± 0.02 MeV was decaying through the 1.309-MeV state. The only known state in this region is the 1.617-MeV state. By comparing the proton spectrum in coincidence with the 1.617-MeV peak with that in coincidence with the 0.638-MeV peak, it was found that the 1.617-MeV state has about a 50% branch to the 1.309-MeV state. This value is the same as the 51% branching ratio given by Engelbertink and Olness.[4] Thus, the fact that the 1.617-MeV state decays about half the time through the 1.309-MeV state appears to be established well beyond the bounds of experimental error.

Transitions of multipolarity other than $M1$ should also be mentioned. All of the $E1$ transitions are weak, usually substantially less than 1% of a single-particle speed. This observation is in accord with a recent survey[19] of this mass region, in which the average $E1$ speed between low-lying states was found to be about 5×10^{-4} W.u. and all reported transitions were slower than 1% of single-particle speed. In ^{40}K the $E2$ transition rates average about single-particle speed, which is quite slow for this region of the Periodic Table.[19] It thus is implied that ^{40}K is close to spherical. A further indication of the lack of collective motion comes from the one $E3$ whose rate was measured and found to be close to single-particle speed. In ^{38}Cl, fewer $E2$ rates are known, since multipole mixing ratios have not been determined. The four $E2$ rates listed in Table IV have an average speed of about 5 single-particle units. Thus it appears that some collective enhancement is present in ^{38}Cl, though probably less than is found in nuclei several nucleons removed from shell closure.

SUMMARY

The picture that describes the low-lying states of ^{38}Cl and ^{40}K as members of rather pure multiplets has had some very noteworthy successes, but there are also some serious failures in the realm of $M1$ transition rates. It has been shown that the inclusion of small admixtures can radically alter the relative intramultiplet $M1$ rates[10, 21] and, in one case at least, can even lead to a fast intermultiplet transition,[10] but the calculations published to date have failed to improve the agreement with experiment. Examination of the entire body of available experimental data leads to the conclusion that it is unlikely that a major portion of the discrepancies can be due to experimental error. Thus, we are forced to conclude that while many of the features of the low-lying states of ^{38}Cl ^{40}K are explained by the simple shell-model picture, some $M1$ transition rates are quite anomalous and appear to defy simple interpretation.

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