A gamma ray study of ^{40}K (using ^{37}Cl(α,n) and ^{40}Ar(p,n))

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A gamma ray study of ^{40}K

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Abstract. The electromagnetic decay scheme of ^{40}K below an excitation of 3·2 MeV has been measured using the $^{37}Cl(\alpha, n)^{40}K$ reaction in conjunction with both a Si(Li)–Ge(Li) and a Ge(Li)–NaI(Tl) coincidence system. Gamma ray angular distribution and angular correlation measurements were also made using both the $^{40}Ar(p, n)^{40}K$ and $^{37}Cl(\alpha, n)^{40}K$ reactions. Four unique spin assignments were made to levels at 2398 keV (4^-), 2419 keV (2^-), 2787 keV (3) and 3147 keV (1). Spin restrictions were placed on other levels, and both branching ratios and multipole mixing ratios determined for several transitions.

A shell model calculation, using the effective surface delta interaction, was performed. The predictions, in good agreement with the present experimental results, showed that the low lying states of positive parity are well described by two particle two hole excitations involving only the $1d_{3/2}$ and $1f_{7/2}$ orbits.

1. Introduction

The low lying negative-parity states of ^{40}K can be reasonably described by a rather simple shell model in which only the $(\pi\ 1d_{3/2}^{-1}, \nu\ 1f_{7/2})$ and $(\pi\ 1d_{3/2}^{-1}, \nu\ 2p_{3/2})$ configurations are considered (Dieperink *et al* 1968, Wechsung *et al* 1971, James *et al* 1971). Positive-parity states described by the $(1d_{3/2}^{-2}, 1f_{7/2}^{2})$ and $(1d_{3/2}^{-4}, 1f_{7/2}^{4})$ configurations are also expected at fairly low excitations, but so far only four states in ^{40}K have been shown to have positive parity (Twin *et al* 1970).

Several experiments have been performed to measure the decay modes, lifetimes and spins and parities of excited states in ^{40}K (Enge *et al* 1959, Wesolowski *et al* 1968, Twin *et al* 1970, Freeman and Gallmann 1970, Johnson and Kennett 1970, James *et al* 1971, Wechsung *et al* 1971, op den Kamp and Spits 1972). Owing to the complexity of the spectra, however, there remain several ambiguities and unknowns. The aim of the present work has therefore been twofold; firstly to elucidate the electromagnetic decay modes and J^{π} quantum numbers of states below an excitation of 3·2 MeV, and secondly to determine the extent to which low lying positive-parity states in ^{40}K can be described by simple shell model configurations.

2. The experimental procedure

In the present series of experiments both the $^{40}Ar(p, n)^{40}K$ and $^{37}Cl(\alpha, n)^{40}K$ reactions were used to populate the excited states of ^{40}K. Natural argon was used as the target in the $^{40}Ar(p, n)^{40}K$ experiments. The gas cell was constructed from two spherically indented sheets of tantalum bonded together. The two indentations had different radii and therefore formed a cavity in which the gas was retained. The beam, from the Liverpool University tandem accelerator, entered the gas cell through a centrally mounted window of 0·013 g cm^{-2} tantalum foil, and passed through 6 mm of gas before stopping on the rear wall. The gas was maintained at a pressure of one atmosphere, and the whole assembly was cooled by cold alcohol circulating through the target mount.

The ^{37}Cl targets, between 1 and 5 mg cm^{-2} thick, consisted of $BaCl_2$ (enriched to 96·5% ^{37}Cl) deposited onto a gold backing.

2.1. Excitation functions

Excitation functions were taken in steps of 100 keV or 200 keV in order to determine reasonably accurate gamma ray thresholds. For the ^{40}Ar(p, n)^{40}K reaction, measurements were made with beam energies in the range 5·30 to 6·10 MeV, whilst for the ^{37}Cl(α, n)^{40}K reaction beam energies between 6·90 and 8·00 MeV were used. All measurements were made with the Ge(Li) detector at 90° to the beam direction so that the gamma ray peaks were not Doppler shifted.

2.2. The gamma–gamma coincidence experiment

Below an excitation of 3 MeV there are five known pairs of levels separated by 30 keV, which is also the separation of the ground and first excited states. To determine those decays proceeding via the first excited state a coincidence was sought between the 30 keV gamma ray and all other gamma rays. The ^{37}Cl(α, n)^{40}K reaction was used at an alpha particle bombarding energy of 8·00 MeV. The 30 keV gamma rays were detected by a 0·5 cm^3 Si(Li) crystal, and other gamma rays in a 35 cm^3 Ge(Li) detector. The Si(Li) crystal was mounted above the target at 90° to the beam axis, and at a distance of 10 mm from the target. The Ge(Li) detector was mounted perpendicular to both the beam axis and the Si(Li) detector, at a distance of 4 cm from the target. The large flux of 11 keV x rays from the gold target backing was reduced by shielding the Si(Li) detector with 0·44 mm thick aluminium foil.

In order to obtain information on other cascades a coincidence was also sought between the Ge(Li) detector and a NaI(Tl) crystal positioned 15 cm from the target at an angle of 0° to the beam direction. All three detectors were shielded from each other by suitable lead blocks.

Conventional fast–slow coincidence techniques were employed. The data were collected event by event and stored on magnetic tape for subsequent off-line analysis. The spectrum from the Si(Li) detector is shown in figure 1. To obtain the required coincidence Ge(Li) spectrum a window was set across the 30 keV peak. Background subtraction was accomplished by setting a window of equivalent width over nearby channels; the resultant spectrum is illustrated in figure 2.

The Ge(Li)–NaI(Tl) experiment was analysed in a similar way, windows being set across peaks seen in the Ge(Li) spectrum to obtain the corresponding coincidence NaI(Tl) spectra. In some cases it was necessary to set a window over a narrow region of the NaI(Tl) spectrum to produce a coincidence Ge(Li) spectrum. In this case meaningful background subtraction could not be accomplished.

2.3. Angular distributions

States under investigation were populated at bombarding energies close to the threshold

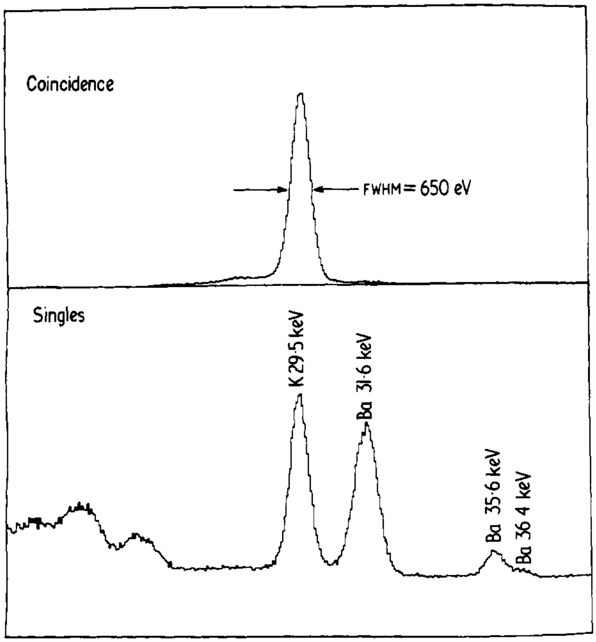

Figure 1. Spectra obtained with the Si(Li) detector. In the upper coincidence spectrum only the 29·5 keV gamma ray from ^{40}K is seen.

for their excitation via the $^{40}Ar(p, n)^{40}K$ reaction. Using a 40 cm^3 Ge(Li) detector the yields of gamma rays de-exciting these levels were measured at angles of 0°, 30°, 45°, 60° and 90° to the beam direction. Precise normalization between the data collected at different angles was obtained from the yield of the 1615 keV gamma ray. This depopulates the spin 0 level at 1·645 MeV in ^{40}K and must therefore be isotropic. The intensities of partially resolved gamma rays were obtained using a peak fitting computer program (Byrne 1970 private communication).

The computer program MANDY (Sheldon and van Patter 1966, Birstein *et al* 1969), which is based upon the compound nucleus statistical model of reactions, was used to predict the range of possible substate populations from the estimated spread in beam energy. Neutron and proton optical model parameters, taken from Wilmore and Hodgson (1964) and Rosen *et al* (1965) respectively, were used to calculate the transmission coefficients required by MANDY. The parameters of Igo (1959) were used for alpha particles. A comparison between measured distributions and a postulated spin sequence was made by a χ^2 analysis. A grid search program performed a stepwise search over permissible values of the mixing ratio and the substate populations of the initial level. A spin hypothesis was rejected if the minimum χ^2 so obtained was greater than the 0·1 % confidence limit. Changing the limits of the range of substate populations by 5 % (roughly equivalent to a change in beam energy of 100 keV to 200 keV) was found to make negligible difference to the best fit. Errors on the multipole mixing ratios were estimated using the method described by Cline and Lesser (1970). The number of degrees of freedom adopted was based on the assumption that the substate populations could be regarded as fixed parameters.

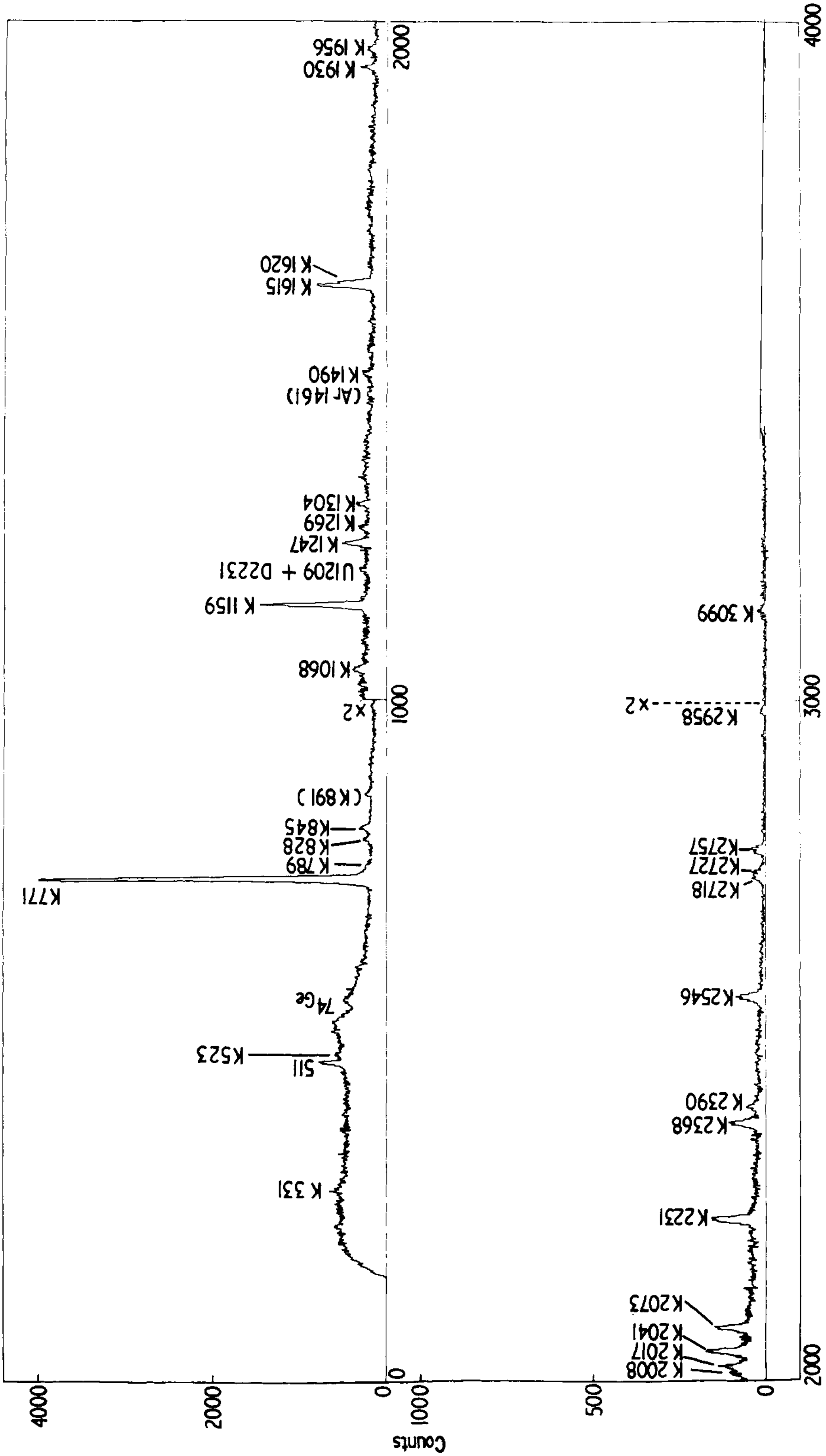

Figure 2. The Ge(Li) spectrum obtained in coincidence with the 30 keV first excited to ground state transition in ^{40}K.

2.4. Gamma–gamma correlations

The two states at 2543 keV and 2879 keV were weakly excited by the ^{40}Ar(p, n)^{40}K reaction but strongly excited by the ^{37}Cl(α, n)^{40}K reaction. Since the ground state of ^{37}Cl has $J = \frac{3}{2}$, states populated by the latter reaction are not strongly aligned even very close to threshold, and this makes unique spin determinations unlikely. Furthermore the primary decays of these levels are not fully resolved in the spectra; a difficulty made worse by Doppler shift and Doppler broadening effects. Gamma–gamma correlations were therefore measured for these two states. The angles defining a point of the correlation are shown in figure 3.

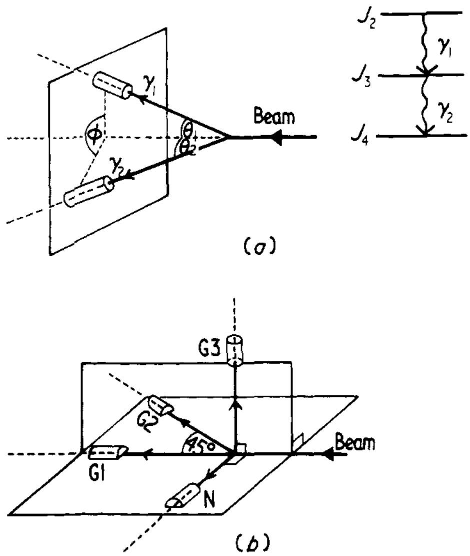

Figure 3. (a) The three angles (θ_1, θ_2, ϕ) which define a point of the angular correlation of a gamma ray cascade ($\gamma_1 \rightarrow \gamma_2$) are shown. The beam direction is taken as the positive z axis. (b) The experimental layout used to measure the correlation of the 336 keV → 1651 keV cascade (from the 2879 keV level) is illustrated. The 336 keV gamma ray was detected in one of three Ge(Li) crystals (G1, G2, G3), and the coincident 1651 keV gamma ray in a NaI(Tl) crystal (N).

The 2543 keV state decays via the 1651 keV–891 keV cascade. The 891 keV gamma ray was detected in one of two Ge(Li) detectors and the coincidence 1651 keV gamma ray in one of five NaI(Tl) crystals. The NaI(Tl) crystals were mounted in the same plane, making angles, θ_1, to the beam axis of 8°, 30°, 45°, 60° and 90°. The Ge(Li) detectors were both mounted at 90° to the beam axis, one in the same plane as the NaI(Tl) array ($\phi = 180°$) and the other perpendicular to this plane ($\phi = 90°$).

The 2879 keV state decays predominantly via the 336 keV–1651 keV–891 keV cascade. Since it is the distribution of the primary decay which is most strongly dependent upon the spin of the initial level, θ_1 is the angle to be varied· Owing to the lack of resolution, however, it was not practical to detect the 336 keV gamma ray in the NaI(Tl) crystals. This gamma ray was therefore detected in three Ge(Li) detectors mounted at angles of 0°, 45° and 90° to the beam axis. The coincident 1651 keV gamma ray was detected in a single NaI(Tl) crystal mounted at 90° to the beam axis as shown in figure 3.

In both experiments event by event data were collected onto magnetic tape, ready for later analysis. The program MANDY was again used to predict the substate populations. As these varied but slowly with beam energy it was possible to fix them in the subsequent χ^2 analysis. The criteria for rejection of a spin hypothesis and the estimation of errors were as described in the previous subsection.

3. The experimental results

The decay scheme of James *et al* (1971) is taken as a basis for the following discussion. In all cases not specifically mentioned here the results of the present experiments (figure 4) are in agreement with those of James *et al.* The most prolific producers of possible decay modes in ^{40}K have been recent neutron capture studies (Johnson and Kennett 1970, op den Kamp and Spits 1972). Comparison between their results and ours is made where appropriate. The level energies, decay modes and branching ratios determined in the present work are summarized in table 1. The level energies quoted are mean energies calculated by means of the Ritz combination principle. Both level energies

Table 1. The level energies of ^{40}K, gamma ray energies and branching ratios determined in the present work

Initial level (keV)	Gamma ray decays (keV)	Branching ratio (%)
1958·8 ± 0·5	1158·9 ± 0·2	82 ± 2
	1929·6 ± 0·2	18 ± 2
2069·7 ± 0·5	1178·4 ± 0·6	3 ± 1
	1268·9 ± 0·6	5 ± 1
	2041·0 ± 0·9	47 ± 3
	2070	45 ± 3
2102·9 ± 0·6	1303·6 ± 0·5	22 ± 4
	2073·1 ± 0·4	78 ± 4
2290·0 ± 0·6	331	8 ± 2
	646·2 ± 0·4	59 ± 4
	1490·3 ± 0·5	33 ± 3
	224	< 2
2291·1 ± 0·2	1400·0 ± 0·4	19 ± 3
	2290·8 ± 0·2	81 ± 3
2397·9 ± 0·3	2367·9 ± 0·3	70 ± 4
	2398·1 ± 0·3	30 ± 4
2419.4 ± 0·4	1619·6 ± 0·2	79 ± 3
	2389·7 ± 0·3	15 ± 2
	2419·4 ± 0·5	6 ± 1
	461	< 2
2542·8 ± 0·4	1651·5 ± 0·5	88 ± 2
	2542·4 ± 1·0	12 ± 2
2575.6 ± 0·5	2546·1 ± 0·2	100
2626·0 ± 0·6	523·3 ± 0·5	70 ± 3
	1826·4 ± 0·2	30 ± 3
	667	< 5
2730·9 ± 0·8	1086·9 ± 0·6	94 ± 4
	1931	6 ± 4
	441	< 12
2747·6 ± 0·3	789 ± 1	4 ± 1
	2717·7 ± 0·2	64 ± 5
	2747·7 ± 0·3	32 ± 3
	678	< 3
2756·2 ± 0·5	1956·0 ± 0·2	66 ± 3
	2727·3 ± 0·3	34 ± 3
2786·6 ± 0·5	827·6 ± 0·25	22 ± 3
	2757·2 ± 0·2	78 ± 3
2787·4 ± 0·3	496·8 ± 0·5	40 ± 8
	1896·3 ± 0·5	19 ± 8
	2787·1 ± 0·25	41 ± 8
2808·2 ± 0·6	2008·5 ± 0·2	100
2879·4 ± 0·5	336·4 ± 0·4	62 ± 4
	1987·8 ± 0·7	38 ± 4
2950·75 ± 0·6	2950·75 ± 0·6	100
2986·6 ± 0·8	2186·2 ± 1·0	15 ± 10
	2958·1 ± 0·6	85 ± 10
3028·1 ± 0·4	737·5 ± 0·5	23 ± 4
	1068·2 ± 0·5	54 ± 5
	3028·8 ± 0·8	23 ± 4
3100·2 ± 0·7	2208·7 ± 0·7	45 ± 10
	3100	55 ± 10
3128·4 ± 0·8	3099	53 ± 10
	3128·4 ± 0·8	47 ± 10
	1081	< 10
3146·7 ± 0·6	1503·1 ± 0·4	33 ± 5
	2346·8 ± 0·2	67 ± 5
3155·1 ± 0·8	3155·1 ± 0·8	100
3230·0 ± 0·7	2428·4 ± 1·0	8 ± 8
	3201·1 ± 1·0	75 ± 6
	3229·4 ± 1·0	25 ± 6

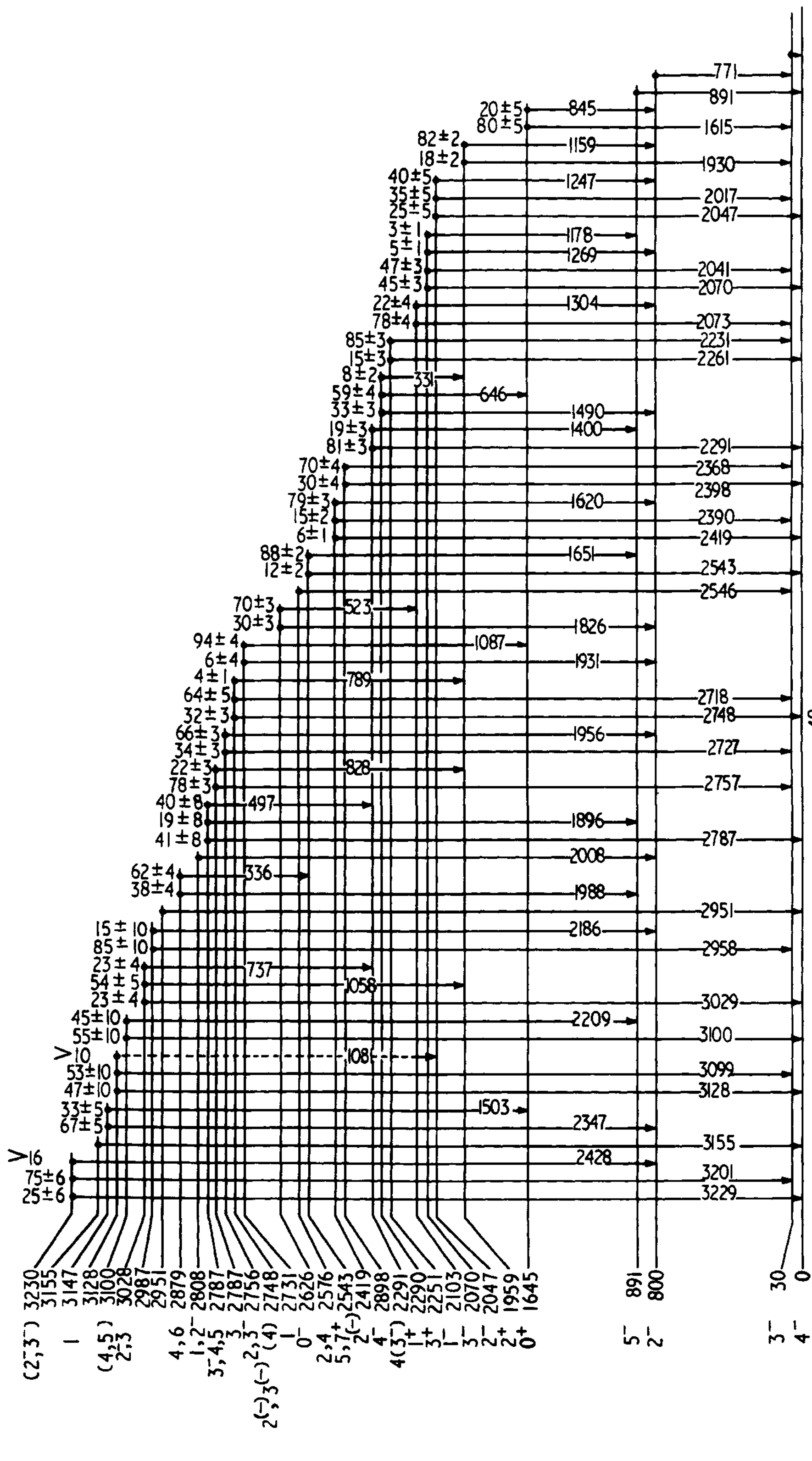

Figure 4. The gamma ray decay scheme of ^{40}K up to an excitation of 3·2 MeV. Results given here but not in tables 1 or 2 were taken from James *et al* (1971).

and gamma ray energies are rounded off to the nearest keV when mentioned in the text. The results of the angular distribution and angular correlation experiments are summarized in table 2, where the a_2 and a_4 coefficients have been corrected for solid angle

Table 2. Results of angular distribution and angular correlation measurements

Initial level (keV)	Final level (keV)	J^π	Gamma ray (keV)	A_2/A_0	A_4/A_0	J^π	Multipole mixing ratio
2290	800	2^-	1490	−0·01 ± 0·01	0·0 ± 0·01	1^+	0·02 ± 0·05
2291	0	4^-	2291	0·39 ± 0·04	−0·03 ± 0·04	3^-	$0{\cdot}6^{+0{\cdot}8}_{-0{\cdot}1}$
						4	$0{\cdot}02^{+0{\cdot}05}_{-0{\cdot}09}$
	891	5^-	1400	0·13 ± 0·11	−0·11 ± 0·12	3^-, 4	—
2398	0	4^-	2398	0·08 ± 0·04	−0·23 ± 0·04	4^-	−2·4 ± 0·5
	30	3^-	2368	0·14 ± 0·04	0·07 ± 0·04	4^-	−0·27 ± 0·06
2419	800	2^-	1620	0·39 ± 0·01	−0·03 ± 0·01	2^-	−1·8 ± 0·2 or −0·07 ± 0·05
	30	3^-	2390	0·31 ± 0·03	−0·01 ± 0·03	2^-	0·8 ± 0·5
	0	4^-	2419	0·13 ± 0·06	0·05 ± 0·06	2^-	$0{\cdot}0^{+0{\cdot}30}_{-0{\cdot}15}$
2543	891	5^-	1651	0·41 ± 0·06†	−0·17 ± 0·07	5	$-1{\cdot}0^{+0{\cdot}4}_{-0{\cdot}2}$
				0·10 ± 0·08‡	0·01 ± 0·09	7^+	0·00 ± 0·13
2576	30	3^-	2546	−0·13 ± 0·02	0·02 ± 0·01	2	0·00 ± 0·03
						4	−0·09 ± 0·04
2731	1645	0^+	1087	−0·33 ± 0·02	−0·01 ± 0·02	1	E1 or M1
2748	0	4^-	2748	0·16 ± 0·13	0·07 ± 0·13	$2^{(-)}$	$0{\cdot}09^{+0{\cdot}08}_{-0{\cdot}12}$
						$3^{(-)}$	$2{\cdot}8^{+0{\cdot}8}_{-0{\cdot}5}$ or 0·27 ± 0·08
						(4)	$0{\cdot}27^{+0{\cdot}09}_{-0{\cdot}15}$
	30	3^-	2718	0·33 ± 0·04	0·07 ± 0·04	$2^{(-)}$	$1{\cdot}2^{+0{\cdot}5}_{-0{\cdot}8}$
						$3^{(-)}$	$0{\cdot}09^{+0{\cdot}09}_{-0{\cdot}18}$
						(4)	−0·36 ± 0·07
2756	30	3^-	2727	−0·10 ± 0·02	−0·02 ± 0·02	2	0·00 ± 0·03
						3^-	$0{\cdot}52^{+0{\cdot}12}_{-0{\cdot}08}$
	800	2^-	1956	0·34 ± 0·02	0·01 ± 0·02	2	0·02 ± 0·07 or $1{\cdot}7^{+0{\cdot}3}_{-0{\cdot}5}$
						3^-	−0·36 ± 0·05
2786·6	30	3^-	2757	0·43 + 0·02	0·0 ± 0·02	3	−0·09 ± 0·11
	1959	2^+	828	−0·44 ± 0·09	−0·11 ± 0·09	3	0·09 ± 0·07
2808	800	2^-	2008	0·07 ± 0·02	0·02 ± 0·02	1	$0{\cdot}09 \leqslant \delta \leqslant 2{\cdot}14$
						2^-	0·27 ± 0·05 or $-5{\cdot}7^{+1{\cdot}4}_{-2{\cdot}4}$
2879	891	5^-	1988	−0·05 ± 0·14	−0·06 ± 0·15	4	0·0 ± 0·2
						6	0·09 ± 0·09
	2543	5, 7	336	—	—	4, 6	$\lvert\delta\rvert \leqslant 0{\cdot}10$
3147	800	2^-	2347	−0·04 ± 0·03	−0·08 ± 0·03	1	−0·1 ± 0·2
	1645	0^+	1503	−0·37 ± 0·09	−0·19 ± 0·10	1	E1 or M1

† Legendre coefficients of the angular distribution of the 1651 keV gamma ray, measured in coincidence with the 891 keV gamma ray detected at $\theta_2 = 90°$ for $\phi = 90°$.
‡ As for † with the coincident 891 keV gamma ray detected in the $\phi = 180°$ plane.

effects. Possible spin and parity assignments, taking account of lifetimes where known, are listed in column seven of this table. The minimum values of χ^2 obtained from various fits to the data are given in table 3. The sign convention used for gamma ray mixing ratios is that of Rose and Brink (1967) and the transition strengths quoted have been calculated using the lifetime measurements of James *et al* (1971).

Table 3. Minimum values of χ^2 found from fits to the present data

Level (keV)	Gamma ray (keV)	Minimum χ^2 for a given spin hypothesis $J = 0$	$J = 1$	$J = 2$	$J = 3$	$J = 4$	$J = 5$	$J = 6$	$J = 7$	$J = 8$	Degrees of freedom	0·1% confidence limit
2291†	2291				1·2	0·8					3	5·4
2291‡	2291				3·1	0·8					3	5·4
2398	2398			13·2	14·1	1·9	15·6				3	5·4
2419	1620			1·1	24·4	57·3					3	5·4
2543	1651					3·5	1·7	3·6	2·6		11	2·8
2576	2546		26·6	2·1	9·1	2·4	200				3	5·4
2731	1087		1·9	369							4	4·6
2747	2718			1·8	2·2	1·2	8·2				3	5·4
2756	1956		35·9	1·6	2·4	28·0					3	5·4
2786·6	828		43·3	96·5	2·9	90·5					3	5·4
2808	2008	5·4									4	4·6
			1·7	1·4	8·3	83·3					3	5·4
2879§	336					1·2	17·6	0·3			4	4·6
2879‖	336							1·0	28·1	0·4	4	4·6
3147	1503		1·3	10·5	18·0						4	4·6

† From the ^{40}Ar(p, n)^{40}K reaction.
‡ From the ^{37}Cl(α, n)^{40}K reaction.
§ The spin of the 2543 keV level was assumed to be 5 for this fit.
‖ The spin of the 2543 keV level was assumed to be 7 for this fit.

3.1. The 2290 keV doublet

The lower member of this doublet at 2290·0 keV decays predominantly to levels at 1645 keV and 800 keV via gamma rays of energy 646 keV and 1490 keV respectively. A further weak branch to the 1959 keV level via a 331 keV gamma ray has been proposed from neutron capture work (Johnson and Kennett 1970, op den Kamp and Spits 1972). This is supported by the present data which show a 331 keV gamma ray in coincidence with the 30 keV transition from the first excited state. The present data contain no evidence of a 244 keV transition to the 2047 keV level as suggested by Johnson and Kennett (1970); the branching ratio would be less than 2%.

As pointed out by Wechsung *et al* (1971) the mixing ratio of the 1490 keV gamma ray and the parity of the lower member of this doublet, as determined by Twin *et al* (1970), are not compatible with the measured lifetime. On measuring this mixing ratio at a proton bombarding energy of 5·3 MeV we find its value to be $\delta = 0{\cdot}02 \pm 0{\cdot}05$. This is compatible with the lifetime of, and a positive-parity assignment to, this level. An alternative value of $\delta = 3{\cdot}1 \pm 0{\cdot}5$ was rejected on transition strength grounds. The M2 strength would be $1{\cdot}6 \pm 0{\cdot}5 \times 10^3$ Weisskopf units (Wu).

For the upper member of this doublet at 2291·1 keV the results of the present work are essentially the same as those of Twin *et al* (1970) and James *et al* (1971), except that for the $J = 4$ hypothesis the mixing ratio of the 2291 keV gamma ray is found to be $\delta = 0{\cdot}02^{+0{\cdot}05}_{-0{\cdot}09}$. This value is supported by a measurement made with the ^{37}Cl(α, n)^{40}K reaction, and by the work of Wechsung *et al* (1971). For the $J = 3$ hypothesis the mixing ratio of the 2291 keV gamma ray ($\delta = 0{\cdot}6^{+0{\cdot}8}_{-0{\cdot}1}$) and the measured lifetime ($\tau_m = 210 \pm 50$ fs) indicate that positive parity is very unlikely (the M2 strength would be greater than 41 Wu).

The results of the present experiments and the work of Twin *et al* (1970) indicate that a $J^{\pi} = 4^{\pm}$ assignment is more probable than $J^{\pi} = 3^{-}$.

3.2. The 2398 keV level

This level decays to the ground and first excited states via gamma rays of energy 2398 keV and 2368 keV respectively. Angular distributions were measured at a proton bombarding energy of 5·3 MeV, 200 keV above threshold. The only fit to the angular distribution of the 2398 keV gamma ray to give a value of χ^2 less than the 0·1 % confidence limit was the $J = 4$ hypothesis. From the lifetime the M2 strength of the 2398 keV gamma ray would be $198^{+\infty}_{-17}$ Wu; thus this level has negative parity.

This spin assignment is in disagreement with the $l_n = 1$ result of Enge *et al* (1959). However, in that experiment the statistics for this level were poor.

3.3. The 2419 keV level

Decays from this level to the 800 keV and 30 keV levels as well as to the ground state are observed. A decay to the 1959 keV level via a 460 keV gamma ray (Johnson and Kennett 1970, op den Kamp and Spits 1972) is not observed in any of the coincidence spectra, and we place an upper limit of 2 % on this branch.

The angular distribution of the 1620 keV gamma ray was measured at a proton bombarding energy of 5·3 MeV, 180 keV above threshold. A χ^2 analysis of this data leads to an unique spin assignment of $J = 2$ for the 2419 keV level. Fitting to the angular distribution of the 2419 keV gamma ray results in two possible values for the mixing ratio, $\delta = 1{\cdot}4^{+0{\cdot}9}_{-0{\cdot}6}$ or $\delta = 0{\cdot}0^{+0{\cdot}30}_{-0{\cdot}15}$. The larger of these would imply an E3 strength of greater than 920 Wu, and is therefore rejected. The alternative of pure quadrupole would give a rather large M2 strength of 4^{+2}_{-1} Wu (Skorka *et al* 1966) indicating that this level is more likely to have negative parity. This is supported by the $l_n = 1$ assignment of Enge *et al* (1959).

3.4. The 2543 keV level

The major decay mode of this level is a 1651 keV gamma ray to the 891 keV level. The coincidence spectrum obtained by setting a window over the 336 keV gamma ray confirms this (figure 5). It also contains a peak at 2·54 MeV. Inspection of the coincidence Ge(Li) spectrum obtained with a window set across the 336 keV peak in the NaI(Tl) spectrum determines the energy of this peak to be 2542·4 ± 1·0 keV. It is therefore the ground state decay of the 2543 keV level.

The angular correlation of the 1651 keV gamma ray in coincidence with the 891 keV transition was measured for two geometries as described in § 2.4. An angular distribution measurement of the 1651 keV gamma ray was also made. Both measurements were made using the $^{37}Cl(\alpha, n)^{40}K$ reaction to populate the 2543 keV level at a bombarding energy of 7·45 MeV. The two correlations and the angular distribution measurements were fitted simultaneously. The mixing ratio of the 891 keV gamma ray was fixed at zero in the analysis. Furthermore since the lifetime of this level has been measured to be 1·5 ± 0·3 ns (Alexander 1972 private communication) the 1651 keV transition may contain an appreciable octupole component. Therefore in the analysis the mixing ratio

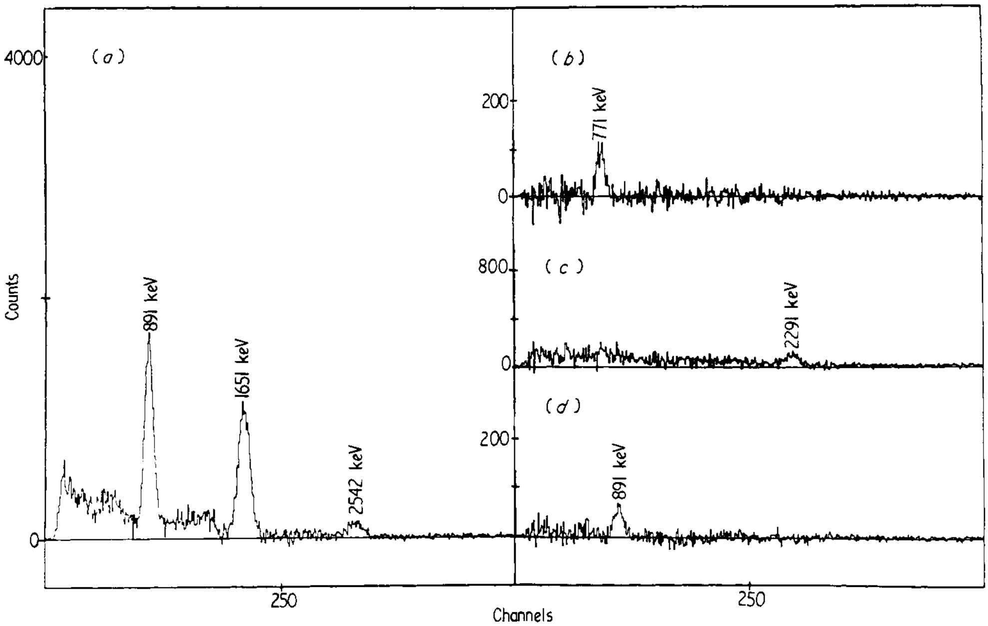

Figure 5. The NaI(Tl) spectra obtained in coincidence with windows set across gamma rays seen in the Ge(Li) spectrum. (*a*) The 2543 keV level: a window set across the 336 keV gamma ray (a decay of the 2879 keV level to the 2543 keV level) shows that the 2543 keV level decays to the ground state via the 2542 keV gamma ray as well as by the 1651 keV → 891 keV gamma ray cascade. (*b*) The 2987 keV level: a window set across the 2186 keV gamma ray confirms the 2186 keV → 771 keV gamma ray cascade from this level. (*c*) The 3028 keV level: a window set across the 737 keV gamma ray shows that this level decays to the upper member of the 2290 keV doublet. (*d*) The 3100 keV level: a window set across the 2209 keV gamma ray confirms the 2209 keV → 891 keV gamma ray cascade of this level.

of the 1651 keV transition was allowed to take all possible values for all spin hypotheses $J = 3$ to 7. The resulting fits enable the hypotheses $J = 4$ and $J = 6$ to be rejected at the 0·1 % confidence level (figures 6 and 7). As pointed out by James *et al* (1971) it is probable that the 2543 keV level has high spin. There are two reasons for believing this. Firstly this level is not populated by the ^{39}K(d, p)^{40}K, ^{39}K(n, γ)^{40}K or ^{40}Ar(p, n)^{40}K reactions, which are not expected to excite levels of high spin. However, the ^{37}Cl(α, n)^{40}K reaction, which can impart more orbital angular momentum to the target, does excite this level. Secondly it is observed to decay only to levels of spin 5^- (891 keV) and 4^- (0 keV). A spin of 5 or 7 is therefore assigned to this level, and if $J = 7$ negative parity is improbable (the M3 strength would be greater than 65 Wu).

3.5. *The 2576 keV level*

The Si(Li)–Ge(Li) coincidence data confirm that this level does decay to the first excited state via the 2546 keV gamma ray as proposed by James *et al* (1971). The angular distribution of the 2546 keV gamma ray was measured at a proton bombarding energy of 5·55 MeV, 170 keV above threshold. A χ^2 analysis of the data gives acceptable fits to the hypotheses $J = 2$ and $J = 4$. These results are similar to those of Twin *et al* (1970) except that for $J = 2$ the mixing ratio found in the present work is $\delta = 0{\cdot}00 \pm 0{\cdot}03$.

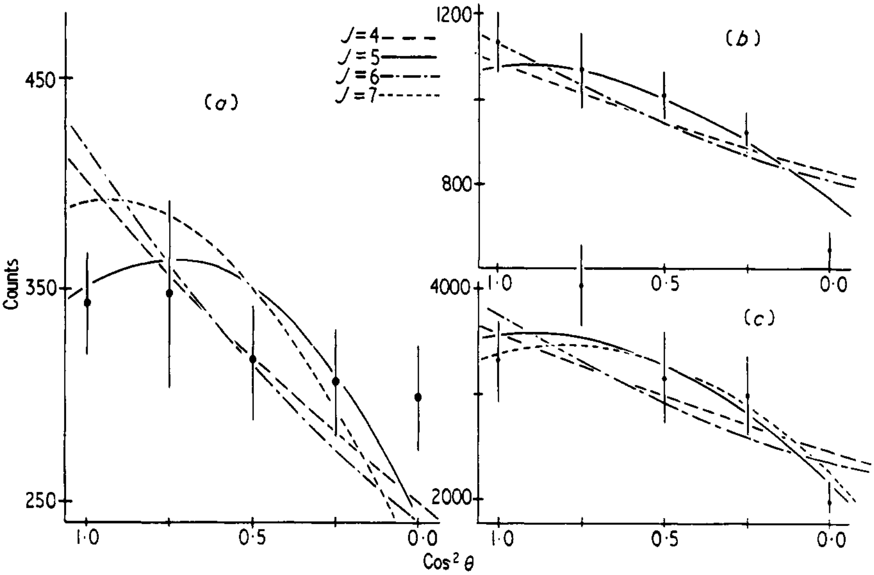

Figure 6. The 2543 keV level in ^{40}K. The angular distributions (*a*) and (*b*) were measured for the 1651 keV gamma ray in coincidence with the 891 keV gamma ray; in (*a*) $\theta_2 = 90°$ and $\phi = 180°$, in (*b*) $\theta_2 = 90°$ and $\phi = 90°$. In (*b*) the fitted curves for $J = 5$ and 7 are the same. (*c*) The measured angular distribution of the 1651 keV gamma ray.

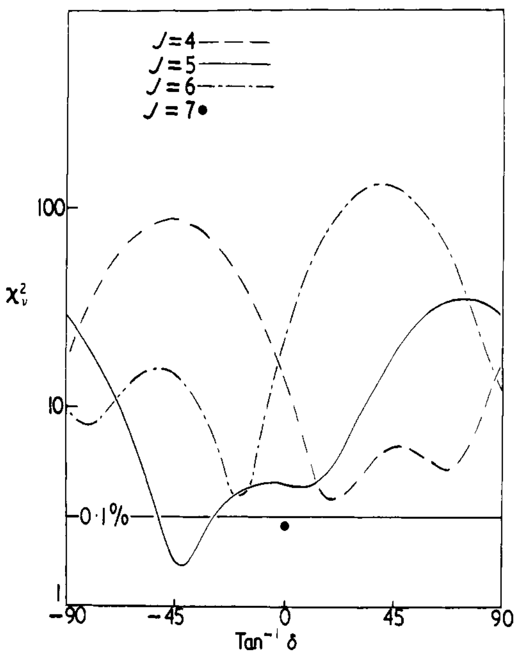

Figure 7. The 2543 keV level in ^{40}K. The result of a simultaneous χ^2 analysis of the data illustrated in figure 6 is shown plotted against $\tan^{-1}\delta$. Both the $J = 4$ and $J = 6$ hypotheses can be rejected at the 0·1 % confidence limit.

3.6. *The 2626 keV level*

The major decay mode of this level is via a 523 keV transition to the 2103 keV level. The possibility that it may also decay via an 1826 keV gamma ray to the 800 keV level (Freeman and Gallmann 1970) is supported by relative intensity measurements made with both the ^{40}Ar(p, n)^{40}K and ^{37}Cl(α, n)^{40}K reactions. In the present work the branching ratio of the 1826 keV gamma ray is measured to be $30 \pm 3\%$ in agreement with Freeman and Gallmann (1970) and with the results of recent neutron capture studies.

3.7. *The 2731 keV level*

This level decays mainly by a 1087 keV transition to the 1645 keV state. Johnson and Kennett (1970) have assigned two other decay modes to this level; a 1931 keV gamma ray to the 800 keV level, and a 441 keV gamma ray to either of the two members of the 2290 keV doublet.

To investigate the proposed 1931 keV transition a window was set over the 771 keV peak in the NaI(Tl) spectrum. The coincidence Ge(Li) spectrum shows a weak 1931 keV gamma ray, giving support to this assignment. A 441 keV gamma ray is not observed in the Si(Li)–Ge(Li) coincidence data, and in the NaI(Tl)–Ge(Li) data it is not possible to distinguish this decay from the 440 keV gamma ray produced by the ^{23}Na(n, n′)^{23}Na reaction. With the aid of the ^{40}Ar(p, n)^{40}K reaction, however, we are able to place an upper limit of 12 % on this branch.

The ^{40}Ar(p, n)^{40}K reaction was used to populate the 2731 keV level 30 keV above threshold. From the angular distribution of the 1087 keV gamma ray an unique spin assignment of $J = 1$ is made to this level. This confirms the assignment of James *et al* (1971) which was based upon the lifetimes.

3.8. *The 2748 keV level*

The data from the present experiments confirm that the major decays of the 2748 keV level are to the ground and first excited states via gamma rays of energy 2748 keV and 2718 keV respectively. From the present data a further assignment of a 789 keV transition to the 1959 keV level is made. The 789 keV gamma ray is seen in both the ^{40}Ar(p, n)^{40}K and ^{37}Cl(α, n)^{40}K reactions with thresholds that support this assignment, and it is also seen in the Si(Li)–Ge(Li) coincidence data. The coincidence data, however, contain no evidence for a 678 keV transition to the 2070 keV level as proposed by James *et al* (1971). From the present data an upper limit of 3 % can be placed on this decay. Removal of this decay will reduce the lifetime of the 2748 keV level as measured by James *et al* (1971).

The angular distribution of the 2718 keV gamma ray was measured at a proton bombarding energy of 5·55 MeV, 20 keV above threshold. A χ^2 fit to the data rules out only the $J = 5$ hypothesis, leaving $J = 2, 3$ or 4 possible. In the stripping reaction ^{39}K(d, p)^{40}K, this level was found to be populated by an $l_n = 1$ transfer (Enge *et al* 1959). Thus a $J = 4$ assignment is not likely to be correct, and the spin of this level is probable 2^- or 3^-. Difficulty was experienced in extracting the angular distribution of the 2748 keV gamma ray, and so the corresponding mixing ratios given in table 2 should be treated as tentative.

3.9. *The 2756 keV and 2787 keV levels*

Previous workers (Johnson and Kennett 1970, James *et al* 1971, op den Kamp and Spits

1972) have proposed levels at 2756 keV and 2787 keV. There is, however, some confusion over their decay modes. For example, from a consideration of transition energies and F factors (ratios of observed gamma ray energy shift to full energy shift in the Doppler shift attenuation method for lifetime measurement), the 2757 keV gamma ray could be a decay from either level. It is clear from the present Si(Li)–Ge(Li) coincidence data, however, that the 2757 keV gamma ray depopulates a level at 2787 keV through the first excited state; see figure 8. The level at 2756 keV decays via 1956 keV and 2727 keV gamma rays to the 800 keV (2^-) and 30 keV (3^-) levels respectively.

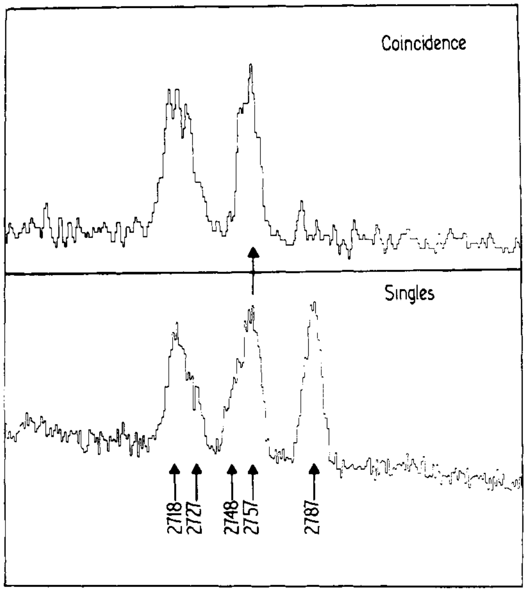

Figure 8. A section of the Ge(Li) spectrum obtained in coincidence with the 30 keV transition in ^{40}K compared with the corresponding section of a singles spectrum; the 2757 keV gamma ray is clearly seen to be in coincidence, and must therefore be a decay to the first excited state.

The angular distribution of the 1956 keV decay of the 2756 keV level was measured at a proton bombarding energy of 5·55 MeV, a mean energy of 10 keV above threshold. Acceptable χ^2 fits are obtained only for $J = 2$ or $J = 3$. For the $J = 3$ hypothesis the M2 strength of the 1956 keV gamma ray would be greater than 240 Wu and therefore a positive parity assignment for this spin can be ruled out. For the $J = 2$ hypothesis the larger value of $\delta = 1{\cdot}7^{+0{\cdot}3}_{-0{\cdot}5}$ yields an E2 strength of greater than 50 Wu so that the alternative value of $\delta = 0{\cdot}02 \pm 0{\cdot}07$ is the more probable.

Using both the $^{40}Ar(p, n)^{40}K$ and $^{37}Cl(\alpha, n)^{40}K$ reactions the relative intensities of the five gamma rays assigned to a level at 2787 keV (James *et al* 1971) were measured. The results (table 4) fall into two groups. On this basis a doublet is proposed: a lower member at 2786·6 ± 0·5 keV decaying mainly via the 2757 keV and 828 keV gamma rays, an upper member at 2787·4 ± 0·3 keV decaying mainly via the 497 keV, 1896 keV and 2787 keV gamma rays. The branching ratios quoted in table 1 assume that the main decay modes are the only ones. The assignment of a 737 keV transition (Johnson and Kennett 1970) from either of these levels is not supported by our measurements. The 737 keV gamma ray is discussed further in § 3.13.

Table 4. Relative intensities of gamma rays from the 2787 keV doublet, as measured using the $^{40}Ar(p, n)^{40}K$ reaction at 5·6 and 5·7 MeV and the $^{37}Cl(\alpha, n)^{40}K$ reaction at 7·6 and 8·0 MeV

Gamma ray energy (keV)	Reaction and bombarding energy (p, n) 5·7 MeV	(α, n) 7·6 MeV	(p, n) 5·6 MeV	(α, n) 8·0 MeV
2787	1	1	1	1
2757	7±1	1·7±0·3	10±2	1·2±0·4
1896	<1·0	0·8±0·1	0·5±0·2	0·5±0·2
828	1·8±0·3	0·6±0·1	2·4±0·4	0·8±0·3
497	—	0·6±0·1	1·0±0·2	0·8±0·1

The measured F factor of the 828 keV gamma ray restricts its mixing ratio to $|\delta| < 0{\cdot}17$ for quadrupole/dipole mixtures (the E2 strength is then less than 300 Wu). Therefore the angular distribution of this gamma ray, measured at 120 keV above threshold was fitted with that restriction on the mixing ratio. Assuming that the 828 keV gamma ray is only associated with the 2786·6 keV level, a unique spin assignment of $J = 3$ can then be made as shown in table 3.

3.10. The 2808 keV level

The present data confirm the decay of this level via a 2008 keV transition to the 800 keV level, as proposed by James *et al* (1971). No other decay modes are observed. The angular distribution of the 2008 keV gamma ray was measured at a proton bombarding energy of 5·70 MeV, 90 keV above threshold. A χ^2 analysis of the data enables all spin hypotheses except $J = 1$ or 2 to be rejected (see table 3). For the $J = 2$ hypothesis positive parity is improbable since the M2 strength would be greater than 20 Wu, and thus $J^\pi = 1^\pm$ or 2^-.

3.11. The 2879 keV level

The data obtained from the present series of experiments are in accord with the 2879 keV level having only two decay modes, as proposed by James *et al* (1971). These are a 336 keV transition to the 2543 keV level and a 1988 keV transition to the 891 keV level.

As described in § 2.4 the angular correlation of the 336 keV–1651 keV gamma ray cascade was measured at an alpha particle bombarding energy of 7·8 MeV. From the lifetime of this level the mixing ratio of the 336 keV gamma ray is restricted to $|\delta| < 0{\cdot}10$ (for an E2 strength of less than 300 Wu) and the possible mixing ratios of the 1651 keV gamma ray are already known (see table 2). With these restrictions on the mixing ratios a χ^2 analysis was carried out for both possible spins ($J = 5$ or 7) of the 2543 keV level. The resulting fits are shown in figure 9. The only spin hypotheses not rejected at the 0·1 % confidence level are $J = 4$, 6 and 8. However the 1988 keV transition to the 891 keV (5^-) level rules out $J = 8$ since it would imply an E3 strength of greater than $9{\cdot}6 \times 10^5$ Wu. As with the 2543 keV level the observation that the 2879 keV level is excited by the $^{37}Cl(\alpha, n)^{40}K$ reaction but not by the $^{40}Ar(p, n)^{40}K$, $^{39}K(d, p)^{40}K$ or $^{39}K(n, \gamma)^{40}K$ reactions and the fact that it only decays to levels of $J \geqslant 5$ suggests that it has high spin. Therefore of the two remaining spin hypotheses $J = 6$ is the more probable.

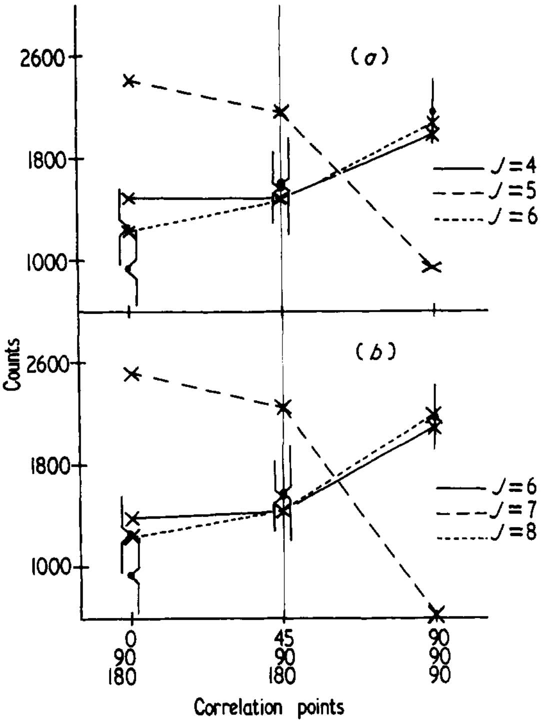

Figure 9. The 2879 keV level in ^{40}K. Fits to the angular correlation of the 336 keV–1651 keV gamma ray cascade are shown for the spin hypotheses indicated for the 2879 keV state combined with (*a*) the $J = 5$ and (*b*) $J = 7$ hypotheses for the 2543 keV level. Correlation predictions are represented by crosses, the lines serving only to guide the eye. The angles defining each point are (from top to bottom) θ_1, θ_2 and ϕ.

An angular distribution measurement of the 1988 keV gamma ray was made using the $^{37}Cl(\alpha, n)^{40}K$ reaction to populate the 2879 keV level at a bombarding energy of 8·0 MeV. For both spin possibilities, $J = 4$ and 6, the mixing ratio determined from this measurement is consistent with $\delta = 0{\cdot}0$.

3.12. The 2987 keV level

That this level decays via the 2186 keV gamma ray is clearly shown by the Ge(Li)–NaI(Tl) coincidence data (figure 5). The Si(Li)–Ge(Li) coincidence data show that a 2958 keV gamma ray decays through the first excited state and thus must arise from a level at 2987 keV. The tentative assignments of James *et al* (1971) are therefore confirmed by the present work.

3.13. The 3028 keV level

James *et al* (1971) assign a single ground state decay from this level. A 3028 keV gamma ray is seen in the present work at the expected thresholds in both the $^{40}Ar(p, n)^{40}K$ and $^{37}Cl(\alpha, n)^{40}K$ experiments. It is not seen in the Si(Li)–Ge(Li) coincidence data, indicating that it is indeed a ground state decay from the 3028 keV level. The Si(Li)–Ge(Li) coincidence data do show a 1068 keV gamma ray. Setting windows over the 771 keV and 1159 keV peaks in the NaI(Tl) spectra the same gamma ray is observed in the corresponding coincidence Ge(Li) spectra. A 1068 keV decay from the 3028 keV level to the 1959 keV level is therefore proposed. Further support comes from the observation that the high energy edge of the 1064/1068 keV doublet has the same threshold as the 3028 keV gamma ray in the $^{40}Ar(p, n)^{40}K$ experiments.

In the Ge(Li)–NaI(Tl) coincidence data a 737 keV gamma ray is observed in coincidence with the 2291 keV gamma ray. This is illustrated in figure 5. It is therefore postulated that the 737 keV gamma ray is a decay from the 3028 keV level to the upper member of the 2290 doublet. This is supported by the F factors of the 737 keV and 3028 keV gamma rays which were measured to be the same.

The measured lifetime limit of the 3028 keV level, $\tau_m < 70$ fs, implies that both the 1068 keV and 737 keV transitions must be dipole (E2 strengths would be greater than 550 Wu and greater than 1530 Wu respectively), and the 3028 keV gamma ray is unlikely to be M2 (its strength would be greater than 50 Wu). Thus the spin of this level is most probably 2^- or $3^\pm$.

3.14. The 3100 keV and 3128 levels

The Ge(Li)–NaI(Tl) coincidence data clearly show that a 2209 keV gamma ray is in coincidence with the 891 keV transition (figure 4). From the Ge(Li)–Si(Li) coincidence data the 3100 keV peak is found to be a doublet consisting of gamma ray transition from (i) the 3100 keV level to the ground state and (ii) from the 3128 keV level to the first excited state. Thus the decay modes of the 3100 keV level are confirmed as those proposed by James *et al* (1971) with the revised branching ratios: 3100 keV ($55 \pm 10\%$), 2209 keV ($45 \pm 10\%$). These branching ratios were extracted from the Si(Li)–Ge(Li) coincidence data on the assumption that angular distribution effects could be neglected.

The 3128 keV level is observed to decay to the ground state as well as to the first excited state in the present work. A possible decay via a 1081 keV gamma ray to the 2047 keV level is confused in the gamma ray spectra by the 1086 keV gamma ray decay from the 2731 keV level to the 1645 keV level, but the apparent threshold of the 1081 keV gamma ray is as would be expected in the $^{40}Ar(p, n)^{40}K$ experiments. It is too weak to be seen in the coincidence data and this decay is therefore regarded as possible but not confirmed.

Gamma ray angular distributions could not be extracted for either the 3100 keV or 3128 keV states. However the spin of the 3100 keV level is restricted to $J^\pi = 3^-$, $4^\pm$, $5^\pm$ or 6^- since both the 2209 keV decay to the 891 keV (5^-) state and the 3100 keV decay to the 0 keV (4^-) state are unlikely to be M2 (their respective M2 strengths would be greater than 200 Wu and greater than 49 Wu). The statistical compound nucleus model of nuclear reactions predicts that the $^{40}Ar(p, n)^{40}K$ reaction will not strongly excite states of $J > 5$ at the bombarding energies used in the present experiments. In the present work the 3100 keV level is seen to be excited by this reaction thus indicating that its spin is $\leqslant 5$. Further, although a level of this energy was not proposed by Johnson and Kennett (1970) or op den Kamp and Spits (1972) the latter authors did see 2207 and 3099 keV gamma rays. It is therefore likely that this level is populated by the $^{39}K(n, \gamma)^{40}K$ reaction also suggesting that its spin is $\leqslant 5$. That this level is not excited by the $^{39}K(d, p)^{40}K$ reaction (Enge *et al* 1959) is not unexpected if it has a 2p2h structure, and hence positive parity, as suggested by the $^{40}Ar(^3He, ^3H)^{40}K$ experiment of Wesolowski *et al* (1968). The above evidence strongly suggests that the spin of the 3100 keV level is 4^+ or 5^+.

3.15. *The 3150 keV doublet*

In the $^{40}Ar(p, n)^{40}K$ experiments gamma rays of energy 1503 keV, 2347 keV and 3155 keV are seen at a threshold which indicates that they arise from a level or levels at about 3·1 MeV. The 3155 keV gamma ray is also seen at the equivalent threshold in the $^{37}Cl(\alpha, n)^{40}K$ experiments. It is not seen in the Ge(Li)–Si(Li) coincidence data indicating that it is a ground state decay, as suggested by James *et al* (1971). The 1503 keV and 2347 keV gamma rays are most probably decays to the 1645 keV (0^+) and 800 keV (2^-) levels respectively (Johnson and Kennett 1970) and thus cannot arise from the same level as the 3155 keV gamma ray. There must, therefore, be a doublet here: a lower member at $3146{\cdot}7 \pm 0{\cdot}6$ keV decaying to the 1645 keV and 800 keV levels via 1503 keV and 2347 keV gamma rays, and an upper member at $3155{\cdot}1 \pm 0{\cdot}8$ keV decaying solely via a 3155 keV transition to the ground state.

The angular distribution of the 1503 keV gamma ray was measured at a proton bombarding energy of 6·10 MeV, 150 keV above threshold. A χ^2 analysis of this data gives an unique spin assignment of $J = 1$ for the 3147 keV level.

3.16. *The 3230 keV level*

This level was assigned three gamma ray decays by Freeman and Gallmann (1970). All three, with energies 3230 keV, 3201 keV and 2428 keV, are seen at the expected threshold in the present $^{40}Ar(p, n)^{40}K$ data, thus supporting these assignments.

The results of a stripping experiment (Enge *et al* 1959) indicate that the 3230 keV level is populated by the $^{39}K(d, p)^{40}K$ reaction via an $l_n = 1$ transfer. Therefore since this level has a decay to the ground state ($J^\pi = 4^-$) it is likely to have a spin of 2^- or 3^-.

3.17. *Other levels below 3·2 MeV*

Five other levels below an excitation of 3·2 MeV have been proposed on the basis of the neutron capture work of Johnson and Kennett (1970). The present experiments have produced no evidence for the suggested levels at 2457 keV, 2557 keV and 2978 keV and are in agreement with the later neutron capture work of op den Kamp and Spits (1972). We find no evidence for decay branches from a level at 2946 keV proposed by both neutron capture studies.

Of the five gamma ray decay modes assigned to a level at 3109 keV by either Johnson and Kennett (1970) or op den Kamp and Spits (1972), only an 1151 keV gamma ray is seen in the present experiments. However, the thresholds observed for this gamma ray in the $^{37}Cl(\alpha, n)^{40}K$ and $^{40}Ar(p, n)^{40}K$ reactions are not consistent with it being a decay mode of ^{40}K. Moreover the intensity balance of the 3109 keV level was poor in both neutron capture studies. We conclude that the present experiments provide no firm evidence for the presence of a 3109 keV level.

4. Discussion

The second aim of the present work has been to determine the extent to which the low lying positive-parity states of ^{40}K can be described by a simple shell model involving only the $1d_{3/2}$ and $1f_{7/2}$ orbits. To this end a shell model calculation was carried out.

The Oak Ridge–Rochester shell model computer program (French *et al* 1969) was used to set up the complete hamiltonian matrix for each (J, T) combination of interest.

A second computer program (Glaudemans 1971 private communication) was used to perform an iterative search procedure, diagonalizing the matrices and looking for the set of one- and two-body reduced matrix elements which gives best agreement with specified experimental level spacings.

Three active orbits, the $1d_{3/2}$, $1f_{7/2}$ and $2p_{3/2}$, were considered. The negative-parity configurations were restricted to no more than one hole in the $1d_{3/2}$ orbit and to no more than one particle in either the $1f_{7/2}$ or the $2p_{3/2}$ orbit. The positive-parity configurations were limited to 0, 2 or 4 particles in the $1f_{7/2}$ shell with correspondingly 0, 2 or 4 holes in the $1d_{3/2}$ shell, with no particles allowed in the $2p_{3/2}$ shell. A further restriction was made that of the particles in the $1f_{7/2}$ orbit no more than two could be unpaired. The largest resultant hamiltonian matrix, for the $J^{\pi} = 3^{+}$, $T = 1$ state, had dimensions of 61×61.

The surface delta interaction (SDI) was chosen to represent the residual interaction. This phenomological interaction has two parameters (Arvieu and Moszkowski 1966). The values of the single particle energies were treated as free parameters. Because fits were made to level spacings this introduced only two extra parameters to give a total of four.

The configuration space chosen for the present calculation will describe states of positive and negative parity in ^{40}K and ^{40}Ca, and positive-parity states in ^{40}Ar. It proved impossible, however, to obtain a reasonable fit to the positive-parity states of ^{40}Ca. This is not unexpected since several of them are known to exhibit collective characteristics. Many of these features were well reproduced by Gerace and Green (1969) using a model which involved deformed states with particles excited into the fp shell. We therefore feel justified in ignoring the positive-parity states of ^{40}Ca. Calculations by Dieperink *et al* (1968) indicate that the present configuration space should provide an adequate description of the lowest 2^{-}, 4^{-} and 5^{-} states of ^{40}Ca. These were therefore included in the data to which the iterative search program fitted. Moreover three positive-parity states in ^{40}Ar were included in the search procedure.

The four known positive-parity states of ^{40}K at 1645 keV (0^{+}), 1959 keV (2^{+}), 2261 keV (3^{+}) and 2290 keV (1^{+}) were fitted. Also used in the fitting procedure were seven 1p1h negative-parity states of ^{40}K at 0 keV (4^{-}), 30 keV (3^{-}), 800 keV (2^{-}), 891 keV (5^{-}), 2047 keV (2^{-}), 2103 keV (1^{-}) and 2626 keV (0^{-}). The 2070 keV (3^{-}) level was not included because the calculation by Dieperink *et al* (1968), as reported by Wechsung *et al* (1971), indicates that this level has a significant admixture of the ($\pi\, 2s_{1/2}^{-1}, \nu\, 1f_{7/2}$) configuration. Thus there were fourteen level spacings from which the four parameters of the model were determined.

In the present calculation no attempt has been made to remove spurious states. However, there is reason for believing that the effects of such states will be small. Since an inert core of thirty-two particles is used with only eight valence nucleons, the centre of mass can be considered as almost at rest. Therefore the effect of spurious states on the calculated level energies is expected to be small.

4.1. *The results of the calculation*

The values of the parameters of the SDI and the single-particle energies (E_{sp}) which produced the best agreement with experimentally known energy levels were:

$$A(T=1) = 0{\cdot}56 \qquad E_{sp}(1d_{3/2}) = 0{\cdot}0\ \mathrm{MeV}$$
$$A(T=0) = 0{\cdot}90 \qquad E_{sp}(1f_{7/2}) = 4{\cdot}9\ \mathrm{MeV}$$
$$E_{sp}(2p_{3/2}) = 6{\cdot}5\ \mathrm{MeV}.$$

The average of the absolute deviations between the experimental and computed energies was 0·10 MeV for the best fit, which we consider to be good for a four parameter fit to fourteen energy level spacings.

Table 5. The experimental and calculated energies of levels used in the fitting procedure

Nucleus	Observed level (MeV)	J^{π}	Calculated energy (MeV)
^{40}Ca	4·49	5^-	4·49
	5·61	4^-	5·69
	6·02	2^-	6·14
^{40}Ar	0·0	0^+	0·0
	1·46	2^+	1·32
	2·52	2^+	2·43
^{40}K	0·0	4^-	0·0
	0·03	3^-	0·06
	0·80	2^-	0·71
	0·89	5^-	0·91
	2·05	2^-	1·82
	2·07	3^-	2·60†
	2·10	1^-	2·19
	2·63	0^-	2·73
	1·64	0^+	1·48
	1·96	2^+	2·17
	2·26	3^+	2·28
	2·29	1^+	2·22

† This level was not used in the fit.

The results of the present calculation for the ($\pi\ 1d_{3/2}$, $\nu\ 1f_{7/2}$) and ($\pi\ 1d_{3/2}$, $\nu\ 2p_{3/2}$) configurations in ^{40}K are given in table 5. The agreement with the experimental spectrum is excellent for the four lowest negative-parity states and fair for the other four. The largest discrepancy occurs for the 3^- level observed at 2070 keV, which has a deviation of 0·53 MeV between the calculated and experimental energies. This anomaly is probably due to the lack of the ($\pi\ s_{1/2}^{-1}$, $\nu\ 1f_{7/2}$) configuration in the present calculation. With a 25 % admixture of this configuration Dieperink *et al* (1968) reproduced the position of the 2070 keV level to within 40 keV.

The present calculation reproduces the energies of the four known positive-parity states at 1645 keV (0^+), 1959 keV (2^+), 2261 keV (3^+) and 2290 keV (1^+) reasonably well. This is shown in figure 10; the largest deviation between theory and experiment is 0·21 MeV for the 2^+ state. The theoretical structure of these states is given in tables 6 and 7. It is immediately apparent from table 6 that they may be described as being predominantly of a 2p2h nature. Inspection of table 7 shows, furthermore, that they can be considered as being formed by recoupling of the two $d_{3/2}$ holes, with the two $f_{7/2}$ particles coupled to $J = 0$.

No other levels in ^{40}K have been shown to have positive parity. The $^{40}Ar(^3He, ^3H)^{40}K$ experiment of Wesolowski *et al* (1968) which is expected to preferentially excite 2p2h states does, however, indicate that states at 2·77 MeV and 3·08 MeV may have positive parity. Also, the level at 2543 keV may be the 7^+ state expected by comparison with ^{42}Sc (James *et al* 1971). Bearing this in mind we can compare the results of the present calculation with our experimental knowledge. This is done in figure 10. A level of

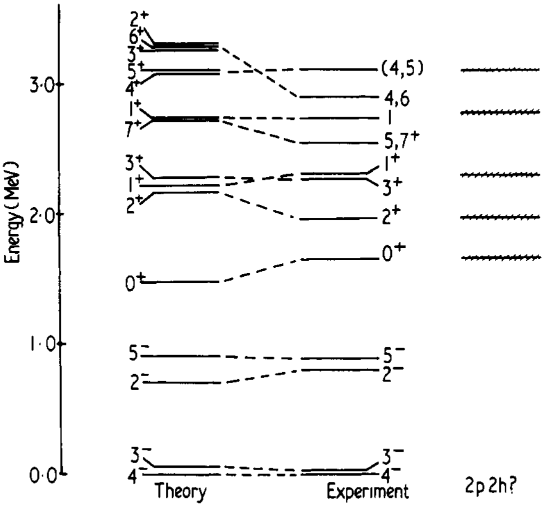

Figure 10. The calculated spectrum of even-parity, $T = 1$ states below 3·2 MeV in ^{40}K is compared with some experimental results, and with the positions of possible 2p2h states as indicated by the $^{40}Ar(^3He, ^3H)^{40}K$ experiment of Wesolowski *et al* (1968). The dashed lines connect levels which may be reasonably associated with each other and do not necessarily imply that they were used in the fitting procedure.

Table 6. Calculated intensities of 2p2h and 4p4h configurations of even-parity states in ^{40}K

State	Intensity of configuration	
J^π	$(d_{3/2}^{-2}, f_{7/2}^2)$	$(d_{3/2}^{-4}, f_{7/2}^4)$
0^+	0·91	0·09
1_1^+	0·93	0·07
1_2^+	0·95	0·05
2^+	0·94	0·06
3^+	0·93	0·07
4^+	0·95	0·05
5^+	0·95	0·05
6^+	0·94	0·06
7^+	0·95	0·05

The subscripts beneath the J^π quantum numbers distinguish the order in which states of the same spin appear in the calculated spectrum.

$J^\pi = 7^+$ is predicted to lie at 2·73 MeV and its only reasonable association is with the 2543 keV level. The wavefunction calculated for this state (table 7) shows, however, that the analogy with ^{42}Sc is only approximate; only 41 % of the wavefunction (by intensity) is actually two $f_{7/2}$ particles coupled to $J = 7$ and two $d_{3/2}$ holes coupled to $J = 0$ whereas the corresponding intensity in ^{42}Sc is 94 % (Flowers and Skouras 1969). If the 2543 keV level has $J^\pi = 7^+$ then the spin of the 2879 keV level is 6 (see table 3). The strength of the 336 keV gamma ray transition between these two levels suggests that they most probably have the same parity. The E1 strength of $3{\cdot}3 \times 10^{-2}$ Wu would be large for this mass region (Skorka *et al* 1966). However, the calculated excitation of the lowest 6^+ states is 3·29 MeV, a discrepancy of 0·41 MeV.

Table 7. Calculated wavefunctions of low lying even-parity states of ^{40}K

State	J of $d_{3/2}$ holes	J of $f_{7/2}$ particles	Intensity of component (%)
0^+	0	0	98·5
	2	2	1·5
1_1^+	0	1	0·6
	1	0	76·0
	1	2	4·4
	2	1	6·0
	2	2	6·3
	2	3	0·0
	3	2	7·0
	3	4	0·0
1_2^+	0	1	78·2
	1	0	5·3
	1	2	0·9
	2	1	9·8
	2	2	1·9
	2	3	3·5
	3	2	0·0
	3	4	0·4
2^+	0	2	5·6
	1	2	2·1
	2	0	78·9
	2	1	7·8
	2	2	0·0
	2	3	1·0
	2	4	0·0
	3	2	4·9
	3	4	0·0
4^+	0	4	49·8
	1	4	7·0
	2	2	22·1
	2	3	7·5
	2	4	0·0
	2	5	4·4
	2	6	0·0
	3	2	2·2
	3	4	6·6
	3	6	0·4
5^+	0	5	16·2
	1	4	4·7
	1	6	0·8
	2	3	8·4
	2	4	31·6
	2	5	5·9
	2	6	0·0
	2	7	0·1
	3	2	21·1
	3	4	11·0
	3	6	0·1
6^+	0	6	61·8
	1	6	10·7
	2	4	9·9
	2	5	7·1
	2	7	6·9
	3	4	0·4
	3	6	3·2
7^+	0	7	41·4
	1	6	6·2
	2	5	1·7
	2	6	23·1
	2	7	17·6
	3	4	3·6
	3	6	6·4

The intensities of the 2p2h components only are given, normalized so that the total intensity is 100%. The subscripts beneath the J^π quantum numbers distinguish the order in which states of the same spin appear in the calculated spectrum.

The predicted position of the second 1^+ state is at 2·74 MeV. A suitable candidate for this state is the observed 2731 keV ($J = 1$) level. This is given support by the observation that the 2731 keV level decays only to the 1645 keV (0^+) level with a strength which indicates that the transition is M1. (The E1 strength would be greater than $0{\cdot}9 \times 10^{-2}$ Wu.) It is possible that the 2731 keV level is the one seen by Wesolowski *et al* (1968) at 2·77 MeV but the discrepancy in the energies is rather large. The wavefunction of this state (table 7) is calculated to be predominantly two $f_{7/2}$ particles coupled to $J = 1$, with the two $d_{3/2}$ holes coupled to $J = 0$. Therefore a corresponding state might be expected in ^{42}Sc, and indeed a $J^{\pi} = 1^{+}$ level is observed 0·61 MeV above the 0^{+} ground state of that nucleus. Higher in excitation the present calculation predicts a 4^{+} state (at 3·07 MeV) and a 5^{+} state (at 3·10 MeV). Either could be associated with the 3100 keV level, the likely spin of which is 4 or 5 (see § 3.14). That there is a level of 2p2h structure of this excitation is indicated by the ^{40}Ar(^{3}He, ^{3}H)^{40}K experiment of Wesolowski *et al* (1968) in which a level at 3·08 MeV was excited. Above this excitation configurations not included in the present calculation are expected to become important besides which the experimental spectrum is not well enough understood to make a meaningful comparison.

The results show that to a good apprxomation the levels in ^{40}K known to have positive parity can be described as 2p2h states in which the two particles are coupled to $J = 0$. Three other observed levels at 2543 keV ($J^{\pi} = 5^{\pm}, 7^{+}$), 2731 keV ($J^{\pi} = 1^{\pm}$) and 3100 keV ($J^{\pi} = 4^{+}, 5^{+}$) can be sensibly associated with predictions of the calculation although, as yet, the experimental spin and parity assignments are not unique. It would therefore seem that below an excitation of 3 MeV simple shell model states of a 2p2h nature, involving only the $1d_{3/2}$ and $1f_{7/2}$ orbits, provide a good description of the positive-parity spectrum of ^{40}K.

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