Level assignment in ^{40}K from polarization measurements (in $^{37}Cl(\alpha,n\gamma)^{40}K$)

1974 J. Phys. A: Math. Nucl. Gen. 7 1985

(http://iopscience.iop.org/0301-0015/7/16/003)

J. Phys. A: Math., Nucl. Gen., Vol. 7, No. 16, 1974. Printed in Great Britain. © 1974

Level assignments in ^{40}K from polarization measurements

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Received 28 May 1974

Abstract. Levels at 2291 keV, 2543 keV, 2786·6 keV and 2879 keV in ^{40}K were studied using the ^{37}Cl (α, nγ)^{40}K reaction at a bombarding energy of 8·0 MeV. Angular distributions and polarizations were measured for transitions from these levels. This polarization information combined with that from earlier angular correlation measurements gives unique assignments of $J^{\pi} = 7^{+}$ for the 2543 keV level and $J^{\pi} = 3^{+}$ for the 2786·6 keV level. The 2879 keV level is established as $J = 6$. Combining the polarization results with those of a single-particle transfer experiment, $J^{\pi} = 3^{-}$ is favoured for the 2291 keV level. Simple shell-model calculations aimed at interpreting the new data are reported.

1. Introduction

The nucleus ^{40}K has recently been the subject of two Doppler shift lifetime studies (James *et al* 1971, Wedberg and Segel 1973) and a comprehensive set of angular correlation experiments (Davies *et al* 1973, to be referred to as I). This paper extends the above angular correlation work to include measurement of the polarization of γ-ray transitions in cases where this measurement is likely to resolve remaining ambiguities in spin and parity assignments.

In particular two such cases are the high-spin states at 2543 keV ($5^{-}, 7^{\pm}$) and 2879 keV (4, 6) which stand out as good candidates for the high-spin positive levels predicted by the shell-model calculation in I. In this experiment the polarizations of transitions from these levels and from those at 2291 keV and 2786·6 keV were measured.

As a result of these angular correlation and polarization studies several new identifications of negative-parity states lying below 2·5 MeV have been made. The success of a simple shell-model calculation in accounting for the spectrum of positive-parity levels (I) prompted calculations of a similar nature aimed at predicting the spectrum of negative-parity levels and evaluating M1 and E2 γ-ray transition strengths between low-lying levels.

2. Experimental method and analysis

A detailed account of the experimental methods used in this work are reported in an earlier paper (Twin *et al* 1974) thus only an outline of the methods are presented. Levels in ^{40}K were populated by the reaction ^{37}Cl(α, n)^{40}K using an 8·0 MeV α particle beam from the University of Liverpool EN generator. Polarization of the γ-rays was measured

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using a triple Ge(Li) Compton polarimeter (Butler *et al* 1973). The definition of polarization used is

$$P = \frac{W(\theta, \phi = 0°) - W(\theta, \phi = 90°)}{W(\theta, \phi = 0°) + W(\theta, \phi = 90°)}$$

where $W(\theta, \phi)$ is the intensity of γ rays at an angle θ to the beam direction with their electric vector at an angle of ϕ to the reaction plane. The polarization sensitivity of this device over a range of γ ray energy 0·7 MeV to 4·4 MeV was determined *in situ* by observing the response to γ rays of known polarization. The relative efficiency of the two absorber detectors was measured before and after the experiment using radioactive sources.

In order to provide information on the alignment of the γ ray emitting state, the angular distribution of the transitions with respect to the beam direction was measured simultaneously using an escape-suppressed spectrometer. Typical spectra are illustrated in the papers of James *et al* (1971) and Twin *et al* (1974).

Data from these two instruments were collected on line by a PDP-7 computer and were written onto magnetic tape for off-line analysis.

The angular distributions were normalized upon the isotropic 1614 keV transition from the 0^+ level at 1644 keV in ^{40}K. The anisotropy of the angular distributions for the transitions of interest indicates that the states are strongly aligned by the reaction although, in this case, stringent limitation of the magnetic substates is not required by conservation of angular momentum. An analysis technique for such situations has been codified (James *et al* 1974) and the data were analysed in this manner.

The set of data for each transition analysed was the γ ray intensities measured at five angles by the spectrometer, the polarization measured at 90° to the beam direction by the polarimeter and a previous determination (from I) of the mixing ratio. Fits to this set of data were made for hypothesized spin and parity assignments for the initial state and the hypotheses tested against the 0·1 % confidence level of a χ^2 distribution of four degrees of freedom. For acceptable hypotheses a best value of the mixing ratio is generated. The phase convention of Rose and Brink (1967) is used throughout the analysis.

3. Results

The measured polarizations and angular distribution coefficients are listed in table 1. This table summarizes the information that enters the fitting program and includes the fitting results. In the subsequent level-by-level discussion use is made of the limitations on spin hypotheses established in I.

3.1. The 2291 keV level

This level decays 81 ± 3 % to the 4^- ground state and 19 ± 3 % to the 5^- level at 891 keV. The results of I, combined with the measured lifetime value of 270 ± 30 fs (Endt and van der Leun 1973) limit the values of J^π to $3^-, 4^\pm$. In this experiment the polarization of the 2291 keV transition was determined to be $-0·67 \pm 0·08$. When the information summarized in table 1 was fitted the hypothesis $J^\pi = 4^-$ was eliminated but both $J^\pi = 3^-$ and 4^+ provided acceptable fits as shown in figure 1. However, in a recent

Table 1. The first three columns list the energies of the states involved and the energy of the transition studied. In the following three columns are given the values of the polarization and angular distribution coefficients measured in this work. The next two columns list appropriate values of the mixing ratio as determined in I. In the final two columns the results of the fit to these data are given in terms of acceptable J^π and δ combinations.

Initial level (keV)	Final level (keV)	Transition energy (keV)	Polarization	a_2/a_0	a_4/a_0	Previous δ	Assumed J^π	Acceptable J^π	δ
2291	0	2291	−0·67±0·08	0·40±0·01	−0·09±0·02	$+0{\cdot}6^{+0{\cdot}8}_{-0{\cdot}1}$	3	3^-	+0·9±0·4
						$0{\cdot}02^{+0{\cdot}05}_{-0{\cdot}09}$	4	4^+	0·02±0·09
2543	891	1652	−0·68±0·08	0·56±0·04	−0·27±0·04	$-1{\cdot}0^{+0{\cdot}4}_{-0{\cdot}2}$	5		
						0·00+0·13	7	7^+	0·00±0·03
2786·6	30	2757	−1·02±0·20	0·35±0·02	−0·01±0·02	−0·09±0·11	3	3^+	$0{\cdot}09^{+0{\cdot}05}_{-0{\cdot}22}$
2879	891	1988	+0·32±0·26	−0·33±0·05	−0·10±0·06	0·09±0·09	6	6^-	$0{\cdot}06^{+0{\cdot}05}_{-0{\cdot}04}$
								6^+	$0{\cdot}06^{+0{\cdot}05}_{-0{\cdot}04}$

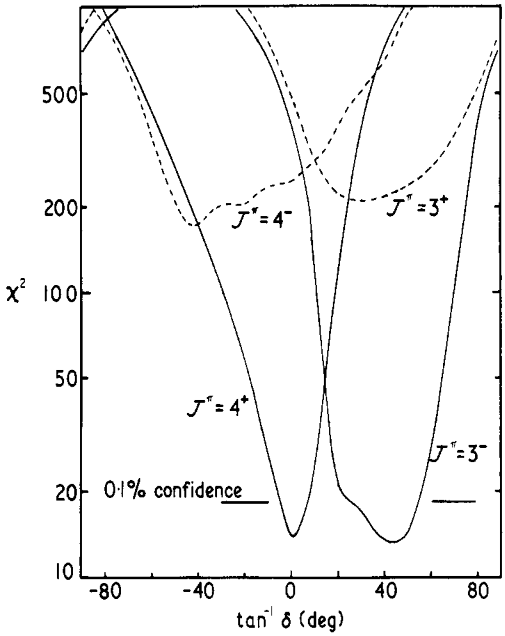

Figure 1. The χ^2 against $\tan^{-1} \delta$ plot for the 2291 keV transition from the 2291 keV level to the 4^- ground state.

study of the $^{39}K(d, p)^{40}K$ reaction (Fink and Schiffer 1974) the stripping to the doublet at this energy indicates that the states have different parity. Since the 2290 keV level is probably $J^\pi = 1^+$ (Twin *et al* 1970) negative parity is indicated for the 2291 keV level favouring an assignment of $J^\pi = 3^-$ and a value of $\delta = +0{\cdot}9 \pm 0{\cdot}4$ for the 2291 keV transition.

3.2. *The 2543 keV level*

This state decays $88 \pm 2\%$ to the 5^- level at 891 keV and $12 \pm 2\%$ to ground. The angular correlation measurements of I and the lifetime determination of $1{\cdot}5 \pm 0{\cdot}3$ ns (Griffiths *et al* 1973) combine to limit the values of J^π to $5^\pm, 7^\pm$. In this experiment the polarization of the 1652 keV transition was measured as $-0{\cdot}63 \pm 0{\cdot}08$. The fits to the information of table 1 are shown in figure 2. The only hypothesis that fits below the 0·1% confidence level is $J^\pi = 7^+$ which is thus assigned to the 2543 keV state. The M2/E3 mixing ratio of the 1652 keV transition was determined to be $\delta = 0{\cdot}00 \pm 0{\cdot}03$.

3.3. *The 2786·6 keV level*

A doublet at 2787 keV was recognized in I by the apparent variation in branching ratio with bombarding energy. The same investigation showed that the lower member of this doublet (at 2786·6 keV) decays principally to the 3^- level at 30 keV and the 2^+ state at 1959 keV, the branching ratios being estimated as $78 \pm 3\%$ for the 2757 keV transition and $22 \pm 3\%$ for the 828 keV γ-ray. Angular correlation measurement on the 828 keV transition resulted in the $J = 3$ assignment for the 2786·6 keV level. In this

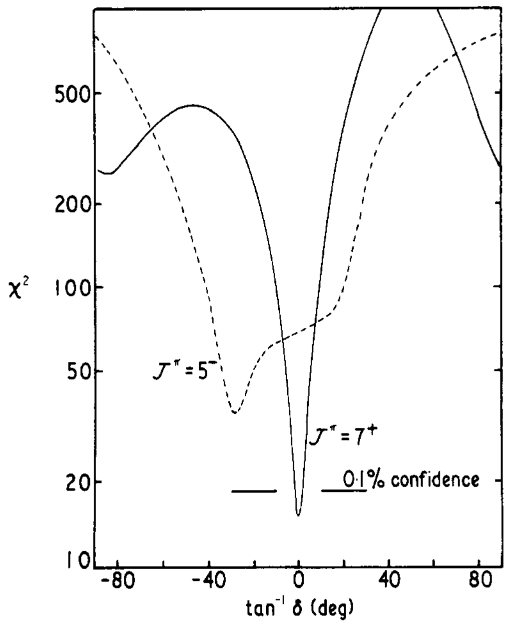

Figure 2. The 2543 keV level. The plot of χ^2 against $\tan^{-1}\delta$ for the 1652 keV transition from the 2543 keV level to the 891 keV 5^- state.

experiment the polarization of the 2757 keV transition was measured as $-1{\cdot}02 \pm 0{\cdot}20$ and in figure 3 fits to the data of table 1 are shown which unambigously assign positive parity. The mixing ratio of the 2757 keV transition is determined as $+0{\cdot}09^{+0{\cdot}05}_{-0{\cdot}22}$.

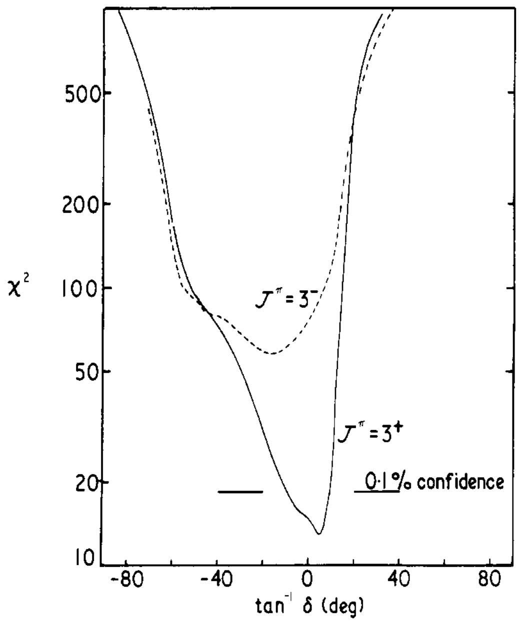

Figure 3. The 2786·6 keV level. The plot of χ^2 against $\tan^{-1}\delta$ for the 2757 keV transition from the 2786·6 keV level to the 30 keV 3^- state.

3.4. The 2879 keV level

The level decays $62 \pm 4\%$ to the 2543 keV 7^+ level and $38 \pm 4\%$ to the 5^- level at 891 keV. A γ–γ correlation measurement of the 336 keV–1652 keV cascade through the 2543 keV level in I combined with the lifetime determination of 390 ± 140 fs results in stringent limitation of the spin of this level. The 2543 keV level having been shown to be $J^\pi = 7^+$, the combination of these results requires that the 2879 keV level be $J = 6$. In this experiment the polarization of the 1988 keV transition was measured as $+0{\cdot}32 \pm 0{\cdot}26$. Fits to the data of table 1 shown in figure 4 indicate that while $J^\pi = 6^+$ is favoured over $J^\pi = 6^-$ both hypotheses fit below the 0·1% confidence level and neither can be excluded.

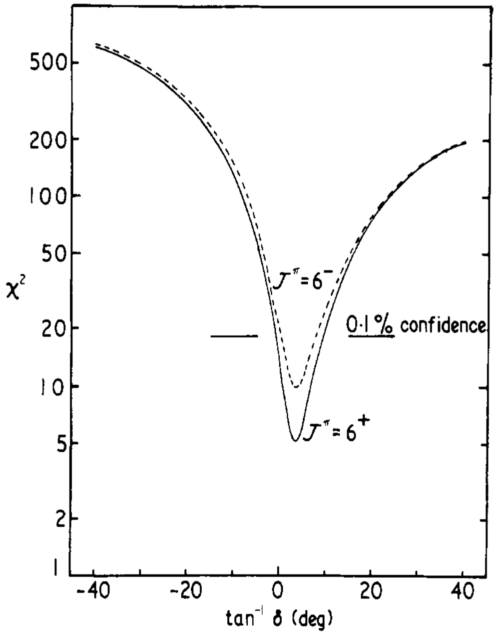

Figure 4. The 2879 keV level. An expanded plot of the region of interest in the χ^2 against $\tan^{-1}\delta$ graph for the 1988 keV transition from the 2879 keV level to the 891 keV 5^- state.

4. Discussion

In I a shell-model calculation involving only $1d_{3/2}$ and $1f_{7/2}$ valence levels was found to reproduce well the energy level spectrum of positive-parity states. In the same spirit simple shell-model calculations were performed aimed at predicting the spectrum of negative-parity levels beyond the $(1d_{3/2})^{-1}(1f_{7/2})$ and $(1d_{3/2})^{-1}(2p_{3/2})$ 'quartets' in order to investigate structures for the newly identified 3_3^- state at 2291 keV and the 4_2^- and 2_3^- states identified at 2398 keV and 2419 keV respectively in I. In addition M1 and E2 transition strengths were evaluated for both positive and negative systems of levels.

4.1. Transitions from positive-parity levels

The wavefunctions used in the evaluation of M1 and E2 transition strengths were essentially those of the two-particle–two-hole and four-particle–four-hole (2p–2h)+(4p–4h) calculations of I. The only difference lay in the use of a program developed by Whitehead (1972) which allowed the full set of (4p–4h) components to be included rather than the truncated set of I. As expected this caused negligible changes in the predicted energy level spectrum. The result of the untruncated calculation is shown at the right of figure 5.

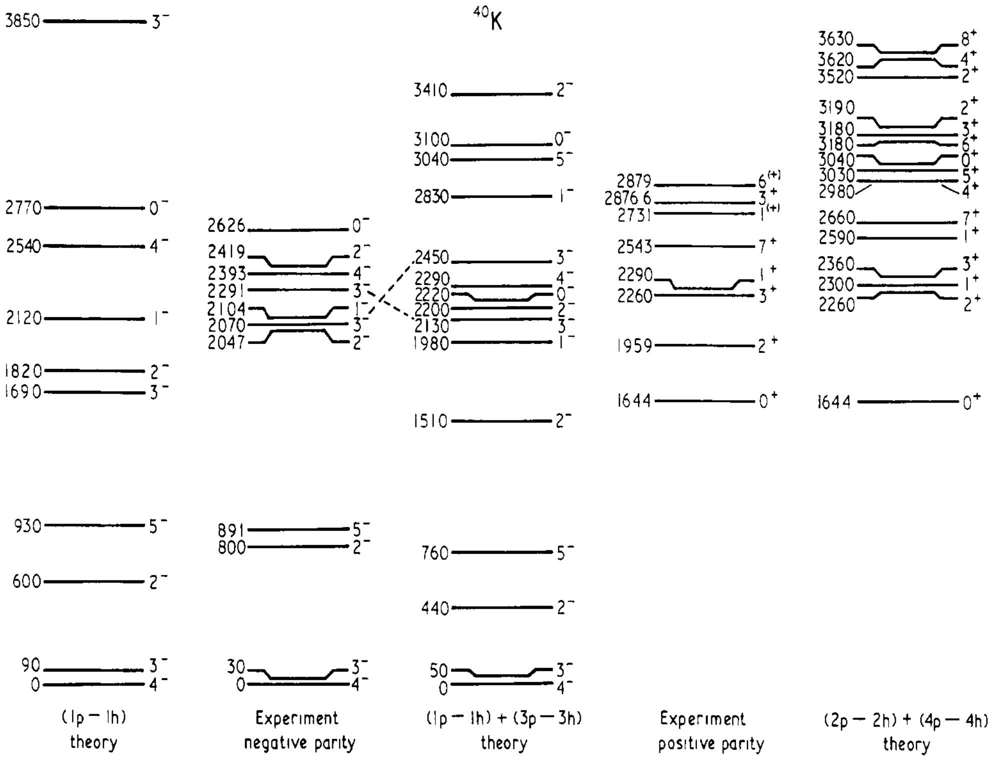

Figure 5. Comparison of calculated level schemes with experiment. Identification between experimental and calculated levels for the evaluation of theoretical transition rates was made by associating an experimental level with the lowest energy theoretical level of the same spin and parity that had not previously been associated. The only exception to this is the association of 3^- states shown by broken lines which is required by the structure of the wavefunctions.

In calculating M1 and E2 strengths an effective charge of 0·5*e* was used (neutron charge = 0·5*e*, proton charge = 1·5*e*) and natural *g* values of $g_n = -3{\cdot}83$ and $g_p = 5{\cdot}59$ were used for neutrons and protons respectively.

The results are compared with experiment in table 2. Only the set of M1 strengths provide a test of the model and here the calculation is successful in predicting the large M1 strengths observed experimentally. More detailed comparison shows some variation from the experimental values but no very large discrepancies.

Qualitative interpretation of E1, M2 and E3 transition strengths is made difficult by the considerable fragmentation of configuration strength over a number of (2p–2h) components for the levels at 2543 keV, 2786·6 keV and 2879 keV.

Table 2. The experimental strengths listed were evaluated using data from the compilation of Endt and van der Leun (1973) supplemented by mixing ratios determined in this work. The theoretical strengths are from the untruncated (2p–2h)+(4p–4h) calculations.

Initial level		Final level		Type of transition	Experimental strength (Wu)	Theoretical strength (Wu)
Energy (keV)	J^π	Energy (keV)	J^π			
2290	1^+	1644	0^+	M1	0.62 ± 0.12	0.08
2290	1^+	1959	2^+	M1	0.62 ± 0.20†	0.82
2543	7^+	0	4^-	E3	2.1 ± 0.5	
2543	7^+	891	5^-	M2	0.18 ± 0.05	
2543	7^+	891	5^-	E3	<3	
2731	$1^{(+)}$	1644	0^+	M1	>0.33	1.5
2786.6	3^+	30	3^-	E1	$(3.8 \pm 1.2) \times 10^{-4}$	
2786.6	3^+	30	3^-	M2	<5	
2786.6	3^+	1959	2^+	M1	0.15 ± 0.05	0.75
2786.6	3^+	1959	2^+	E2	<24	0.07
2879	$6^{(+)}$	891	5^-	E1	$(1.03 \pm 0.29) \times 10^{-4}$	
2879	$6^{(+)}$	891	5^-	M2	<6	
2879	$6^{(+)}$	2543	7^+	M1	1.34 ± 0.38	0.48
2879	$6^{(+)}$	2543	7^+	E2	<390	0.13

† Pure M1 assumed.

4.2. The spectrum of negative-parity levels

Two calculations were performed attempting to account for the spectrum of negative-parity levels. In each case the SDI interaction (Glaudemans *et al* 1967) was used with the full set of states possible for the given numbers of particles and holes in the designated single-particle levels.

In the first calculation only one-particle–one-hole (1p–1h) configurations were considered with the hole occupying the $2s_{1/2}$ or $1d_{3/2}$ levels and the particle the $1f_{7/2}$ or $2p_{3/2}$ states.

In the second calculation one-particle–one-hole and three-particle–three-hole (1p–1h)+(3p–3h) configurations were allowed, the hole(s) being limited to the $1d_{3/2}$ level while the particles were allowed to occupy the $1f_{7/2}$ and $2p_{3/2}$ states without restriction.

The five parameters of the (1p–1h) calculation (isoscalar and isovector strengths of the SDI interaction plus three energy differences of single-particle levels) were fitted to 11 energy level differences of states in ^{40}Ca and ^{40}K. The states chosen in ^{40}Ca were those at 4491 keV (5^-), 5614 keV (4^-), 5902 keV (1^-) and 6025 keV (2^-). In ^{40}K the levels were those of the '$(1d_{3/2})^{-1}(1f_{7/2})$ quartet' 0 keV (4^-), 30 keV (3^-), 800 keV (2^-) and 891 keV (5^-), the '$(1d_{3/2})^{-1}(2p_{3/2})$ quartet' 2047 keV (2^-), 2070 keV (3^-), 2104 keV (1^-) and 2626 keV (0^-) and the 4_2^- level at 2398 keV.

The energy level spectrum predicted by this calculation is shown at the left of figure 5.

The program that allowed an untruncated basis of states in the (1p–1h)+(3p–3h) calculation did not allow fitting of the four parameters of the model to experimental data. Accordingly SDI parameters determined for the earlier calculation of I were used (isoscalar strength $A_0 = 0.90$ MeV, isovector strength $A_1 = 0.56$ MeV) since this fit to 14 negative- and positive-parity levels in ^{40}Ar, ^{40}Ca and ^{40}K involved the same single-particle levels. In the present calculation it was found necessary to reduce the values of the single-particle energy level differences to $E_{f_{7/2}}-E_{d_{3/2}} = 3{\cdot}5$ MeV and $E_{p_{3/2}}-E_{f_{7/2}} = 1{\cdot}6$ MeV to compress the theoretical spectrum into optimum agreement with experiment. The spectrum generated by this calculation is shown at the centre of figure 5.

This figure shows that both calculations are reasonably successful in predicting the energies of the low-lying 'quartet' states and that both can account for a low-lying 4_2^- level. (In the case of the 1p–1h model a check showed that this was the case whether or not the 2398 keV 4_2^- level is used in the data used to fix the model parameters.) While the (1p–1h)+(3p–3h) model is also successful in predicting low-lying 3_3^- and 2_3^- levels as candidates for the states at 2291 keV and 2419 keV, in the (1p–1h) model these states come much higher in energy.

The wavefunctions for the lower 'quartet' of states are dominated by the configuration $(1d_{3/2})^{-1}(1f_{7/2})$ in both calculations and those for the upper 'quartet' by $(1d_{3/2})^{-1}(2p_{3/2})$ structure except for the 3_2^- state. In the (1p–1h) calculation this state is made up of approximately equal intensities of $(1d_{3/2})^{-1}(2p_{3/2})$ and $(2s_{1/2})^{-1}(1f_{7/2})$ configurations while for the (1p–1h)+(3p–3h) model the 3^- state predicted at 2·13 MeV is dominated by (3p–3h) structure and the 3^- level predicted at 2·45 MeV is composed of approximately equal intensities of $(1d_{3/2})^{-1}(2p_{3/2})$ and (3p–3h) components. These structures are not in good agreement with the $^{39}K(d, p)^{40}K$ stripping results of Enge *et al* (1959) who observed a strong $l = 1$ transition to the 2070 keV 3_2^- level and only weak formation of the 2291 keV level.

Table 3. In the comparison between experimental and predicted transition strengths the experimental strengths were evaluated using data from the compilation of Endt and van der Leun (1973) supplemented by mixing ratios from I and the present work. The theoretical values are from the (1p–1h)+(3p–3h) calculation.

Initial state		Final state		Experimental strength (Wu)		Theoretical strength (Wu)	
Energy (keV)	J^π	Energy (keV)	J^π	M1	E2	M1	E2
30	3^-	0	4^-	$0{\cdot}20 \pm 0{\cdot}01$		0·07	
800	2^-	30	3^-	$0{\cdot}14 \pm 0{\cdot}02$	$<0{\cdot}09$	0·09	0·0008
891	5^-	0	4^-	$0{\cdot}034 \pm 0{\cdot}005$	$1{\cdot}8 \pm 1{\cdot}6$	0·035	2·4
2047	2^-	0	4^-		$1{\cdot}1 \pm 0{\cdot}2$		0·23
2047	2^-	30	3^-	$(1{\cdot}7 \pm 0{\cdot}2) \times 10^{-3}$	$<2{\cdot}4 \times 10^{-3}$	$1{\cdot}0 \times 10^{-4}$	1·8
2047	2^-	800	2^-	$0{\cdot}010 \pm 0{\cdot}001$	$0{\cdot}26 \pm 0{\cdot}20$	0·02	0·14
2070	3^-	0	4^-	$(1{\cdot}5 \pm 0{\cdot}3) \times 10^{-3}$	$(6 \pm 6) \times 10^{-3}$	3×10^{-3}	$1{\cdot}4 \times 10^{-5}$
2070	3^-	30	3^-	$(2{\cdot}0 \pm 0{\cdot}4) \times 10^{-3}$	$0{\cdot}11 \pm 0{\cdot}07$	0·03	0·6
2070	3^-	800	2^-	$(1{\cdot}0 \pm 0{\cdot}2) \times 10^{-3}$	$0{\cdot}05 \pm 0{\cdot}04$	4×10^{-3}	0·08
2070	3^-	891	5^-		$1{\cdot}3 \pm 0{\cdot}5$		0·3
2103	1^-	30	3^-		$2{\cdot}4 \pm 0{\cdot}3$		1·2
2103	1^-	800	2^-	$(4{\cdot}4 \pm 0{\cdot}6) \times 10^{-3}$	$0{\cdot}7 \pm 0{\cdot}3$	3×10^{-3}	1·8
2291	3^-	0	4^-	$(4{\cdot}3 \pm 1{\cdot}8) \times 10^{-3}$	2 ± 1	3×10^{-3}	0·09
2291	3^-	891	5^-		14 ± 2		0·23
2398	4^-	0	4^-	$(2{\cdot}0 \pm 1{\cdot}0) \times 10^{-3}$	$6{\cdot}7 \pm 2{\cdot}7$	0·1	0·08
2398	4^-	30	3^-	$0{\cdot}03 \pm 0{\cdot}01$	$1{\cdot}4 \pm 0{\cdot}8$	3×10^{-3}	0·07
2419	2^-	0	4^-		$0{\cdot}07 \pm 0{\cdot}04$		0·03
2419	2^-	30	3^-	$(2{\cdot}0 \pm 1{\cdot}3) \times 10^{-4}$	$0{\cdot}08 \pm 0{\cdot}07$	7×10^{-3}	0·03
2419	2^-	800	2^-	$0{\cdot}05 \pm 0{\cdot}03$	$0{\cdot}03 \pm 0{\cdot}03$	0·06	0·02
2626	0^-	800	2^-		$4{\cdot}6 \pm 0{\cdot}9$		2·8
2626	0^-	2103	1^-	$0{\cdot}42 \pm 0{\cdot}08$		0·7	

The structure of the 4_2^- level is principally $(2s_{1/2})^{-1}(1f_{7/2})$ in the (1p–1h) calculation and in the (1p–1h)+(3p–3h) model it is of (3p–3h) nature as is the low-lying 2_3^- level predicted at 2·20 MeV.

4.3. *Transitions between negative-parity states*

Calculation of M1 and E2 γ-ray transition rates between negative-parity states provides a more sensitive test of the model wavefunctions than is afforded in predicting the energy level spectrum. The strengths were calculated for the (1p–1h)+(3p–3h) model only using an effective charge of 0·5e and natural g values. The results are compared with experimental values in table 3.

The calculation is successful in reproducing the experimental situation that M1 strengths are, on average, much weaker between negative-parity levels than between the positive-parity levels of table 2. As expected the best detailed agreement between theory and experiment occurs for transitions between levels of principally (1p–1h) nature; the only case of gross disagreement occurring for the transitions from the 2047 keV 2_2^- state to the 30 keV 3_1^- level. For non-quartet levels the transition rates calculated for the 2_3^- level predicted at 2·20 MeV are in reasonably good agreement with those measured from the 2419 keV 2^- level but the agreement between transition strengths from the levels predicted at 2·13 MeV (3^-) and 2·29 MeV (4^-) and the experimental strengths measured from the 2291 keV 3^- and 2398 keV 4^- levels is not so good.

In summary although there are discrepancies in detail these simple shell-model studies reproduce the main features of the measured energy levels and transition strengths and should prove useful as a guide to the states to be expected at higher energies in ^{40}K.

Acknowledgments

The work was financially supported by the UK Science Research Council.

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