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Gamma-ray Studies using a Solid Argon Target: Properties of States in ^{40}K and ^{40}Ar†

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Abstract

The Doppler shift attenuation method was used to deduce lifetimes of levels in ^{40}Ar and ^{40}K populated by the reactions ^{40}Ar(p, n)^{40}K and ^{40}Ar(p, p′)^{40}Ar. Spins and mixing ratios in ^{40}K were also deduced from angular distribution measurements. The target used was solid argon at a temperature of 66 K. Substantial agreement with other recent work has been found. The results are interpreted using a weak coupling calculation and a simple δ function interaction model.

Introduction

Nucleon transfer reactions (Enge *et al.* 1959; Betts *et al.* 1975) have established that the four lowest lying states of ^{40}K at 0, 30, 800 and 891 keV arise mainly from the $\pi\, d_{3/2}^{-1}\, \nu\, f_{7/2}$ configuration of the *j–j* coupling shell model, and that the states at 2069 and 2397 keV have significant $\pi\, s_{1/2}^{-1}\, \nu\, f_{7/2}$ components, while the states at 2047, 2069, 2104 and 2626 keV contain the major components of the $\pi\, d_{3/2}^{-1}\, \nu\, p_{3/2}$ particle–hole configuration. Although nucleon transfer reactions examine very directly the major configuration of a nuclear state they are usually insensitive to small admixtures of other configurations. A very sensitive method of testing for these small admixtures is the examination of electromagnetic transition rates.

Transition strengths between the odd-parity states have been most recently calculated by Becker and Warburton (1971) who also referenced earlier calculations. They showed that the most important contaminants of the $\pi\, d_{3/2}^{-1}\, \nu\, f_{7/2}$ wavefunctions arose from the $\pi\, d_{3/2}^{-1}\, \nu\, f_{5/2}$ and $\pi\, d_{5/2}^{-1}\, \nu\, f_{7/2}$ configurations. More recently Davis *et al.* (1973) performed a shell model calculation which described the low lying even-parity states of ^{40}K using the $1d_{3/2}$, $1f_{7/2}$ and $2p_{3/2}$ orbits. Using the surface δ function interaction and treating the single-particle energies as free parameters, they fitted 14 energy level spacings from 17 levels in ^{40}Ar, ^{40}Ca and ^{40}K, and reproduced the energies of the four known even-parity states at 1643 (0^+), 1959 (2^+), 2261 (3^+) and 2290 keV (1^+) with a maximum error of 210 keV. Davis *et al.* found that these states were mainly 2 particle–2 hole $d_{3/2}^{-2} f_{7/2}^{2}$ configurations.

Because of the earlier interest we decided in 1971 to measure lifetimes, mixing ratios and branching ratios in ^{40}K. As a proton beam was the only accelerated beam available to us, we decided to attempt Doppler shift attenuation method (DSAM) measurements of lifetimes in ^{40}K using the ^{40}Ar(p, n)^{40}K reaction. Since most of the lifetimes are considerably shorter than the characteristic slowing-down time in a gas, we attempted to use a solid argon target. We were successful in this and were thus

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able to measure (or obtain limits on) the lifetimes of all levels in ^{40}K excited by the (p, n) reaction up to an excitation energy of 2808 keV. Lifetimes of some levels in ^{40}Ar were also obtained. The alignment achievable with the ^{40}Ar(p, n)^{40}K reaction exceeds that for the ^{37}Cl(α, n)^{40}K reaction used in other studies ($J_p + J_t = 1/2$, while $J_\alpha + J_t = 3/2$, where J_t is the spin of the target). We therefore undertook to measure the angular distributions of the γ rays de-exciting the levels in ^{40}K in order to obtain information on spin assignments and multipole mixing ratios. These data were obtained at the same time as we recorded the DSAM measurements.

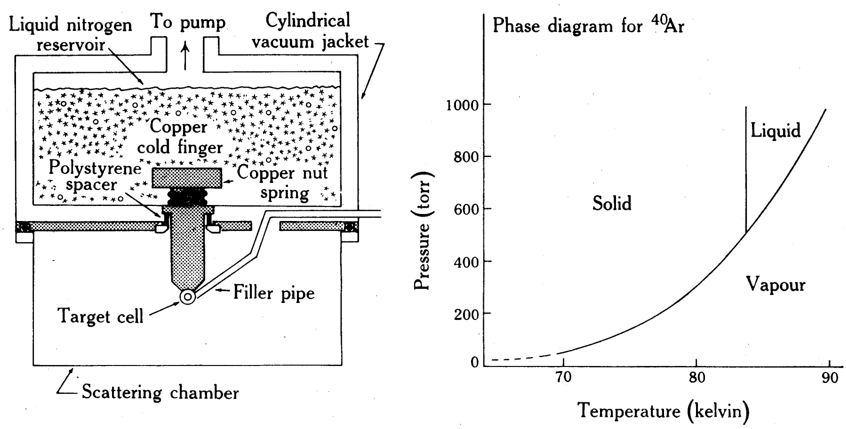

Fig. 1. Cryogenic assembly for the solid argon target used in the present experiment, together with the phase diagram for ^{40}Ar. The nut and spring maintain pressure on the vacuum seal. The argon pressure was held at 516 torr as the temperature was lowered, to ensure a uniform target density free from voids. The operating temperature and pressure were 66 K and 516 torr respectively.

A preliminary report of the present measurements has already appeared (Poletti and Beale 1972) and during this work other recent measurements of lifetimes (Wechsung *et al.* 1971; James *et al.* 1971; Wedberg and Segel 1973) and multipole mixing ratios (Twin *et al.* 1970; Wechsung *et al.* 1971; Davis *et al.* 1973) have been published. Agreement between experimental groups is generally good, and best estimates of lifetimes and branching ratios have been obtained by appropriately averaging the various sets of results.

Experimental Technique

The target material (as shown in Fig. 1) was contained in a 0·6 cm diameter copper cell on the end of a copper rod in good thermal contact with liquid nitrogen held in a reservoir above the target chamber. The proton beam from the University of Auckland tandem Van de Graaff accelerator entered the cell through a 6·4 μm thick nickel window (310 keV thick to 5·5 MeV protons) glued to its front face. Careful attention to the physical state of the target material was necessary, because an essential parameter in the lifetime analysis was the density of the stopping material. The argon in the cell was carefully kept in the solid phase at 66 K by pumping on the liquid nitrogen reservoir. It can be seen from the phase diagram for argon also shown in Fig. 1 that, in order to ensure a reproducible and constant density of target material, the pressure in the cell must be kept above 516 torr (68·8 kPa) as the temperature of

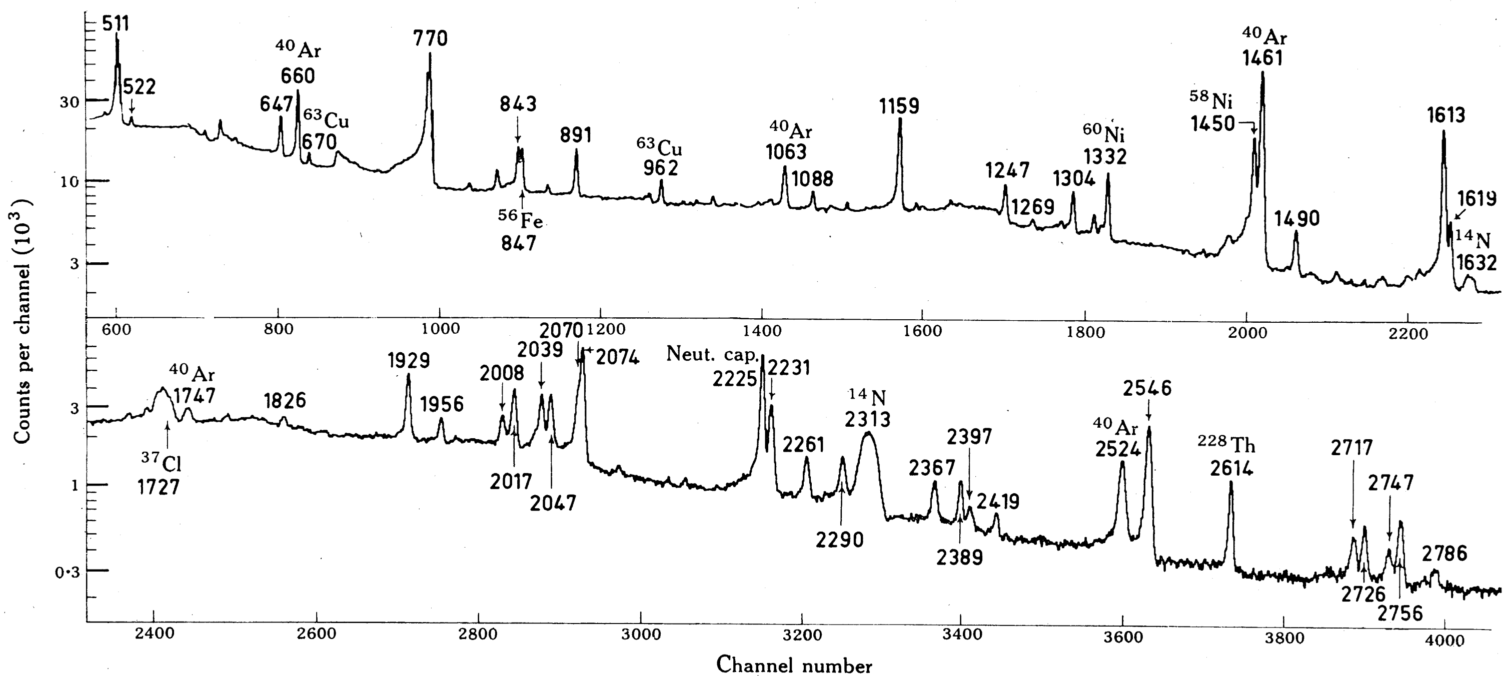

Fig. 2. A 4096 channel spectrum observed with a Ge(Li) detector at 90° to the beam direction. The proton bombarding energy was 5·75 MeV. Those peaks labelled with energy only were produced by decays in ^{40}K. The 770 keV peak, produced by the decay of the 800 keV level to the first excited state of ^{40}K, has been truncated at approximately one-half of the full peak height.

the argon gas is lowered to its freezing point. This ensures that the liquid phase is encountered before freezing. Temperatures below 66 K were precluded by solidification of the liquid nitrogen, with a consequent loss of thermal conductivity to the cold finger but, at 66 K and with a maximum beam current of 2 nA, no effects due to melting of the target were observed. Singles γ-ray spectra were accumulated at six angles (0°, 30°, 45°, 60°, 90° and 135°) with respect to the beam direction. Five bombarding energies (3·57, 4·95, 5·15, 5·40 and 5·75 MeV) were used so that each level could be excited at two energies, typically 120 and 300 keV above threshold. Determination of the mixing ratio for a particular decay involves measurement of the γ-ray yield as a function of detection angle only. This yield from a state being excited near threshold also depends sensitively on the beam energy, which must therefore be constant.

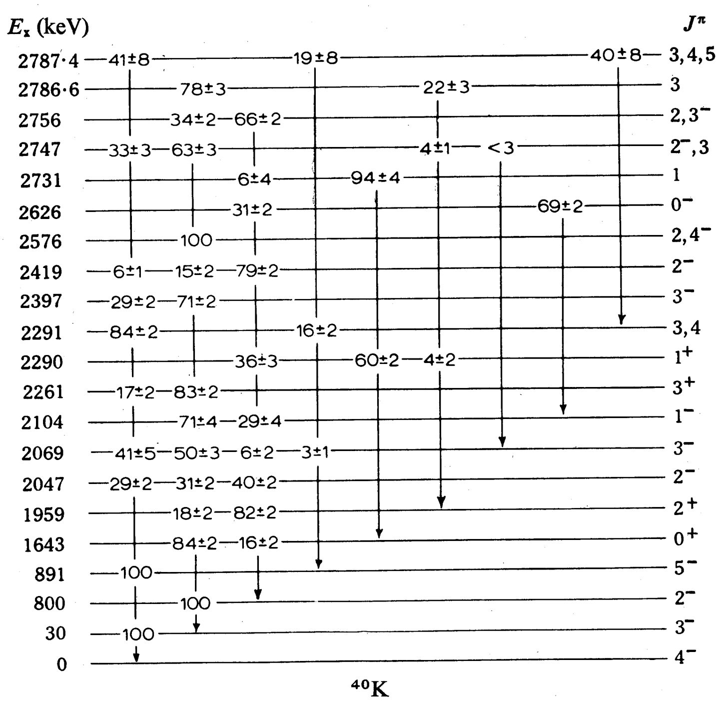

Fig. 3. Levels in ^{40}K. The energies shown are rounded from those measured in the present experiments, and the decay modes are averages as discussed in the text. However, the energies and decay modes of the two highest levels are from Davis *et al.* (1973) alone.

Residual gas in the vacuum system condensing onto the target window could substantially lower the effective bombarding energy. Consequently care was taken to minimize this effect and ensure a high vacuum of 10^{-6} torr ($1 \cdot 3 \times 10^{-4}$ Pa) in the target chamber. No systematic decrease in yield was then detected but nevertheless several spectra were accumulated at each angle and the measurements at different angles were taken in random order to nullify any residual effect. Subsequently the spectra (typically five) taken at the same angle were added together before peak areas and positions were determined. Gain drifts were monitored by observing the positions of the 2614 keV γ ray from a ^{228}Th source and the 661 keV γ ray from the decay of the 2122 keV level in ^{40}Ar. The 2122 keV level has a long lifetime (Endt and van der Leun 1973) of 80 ± 40 ps, and hence the 661 keV γ ray was not Doppler shifted in these experiments. Typical drift was less than 4 channels in 4000 for the duration of a series of measurements at a particular energy. Before addition and analysis, all related spectra were scaled to the same gain using the monitor peaks. The detector, a Ge(Li) γ-ray spectrometer, had an efficiency of 10% and a resolution of 3 keV (FWHM) at 1·33 MeV under the experimental conditions. Its front face was 16·5 cm from the target.

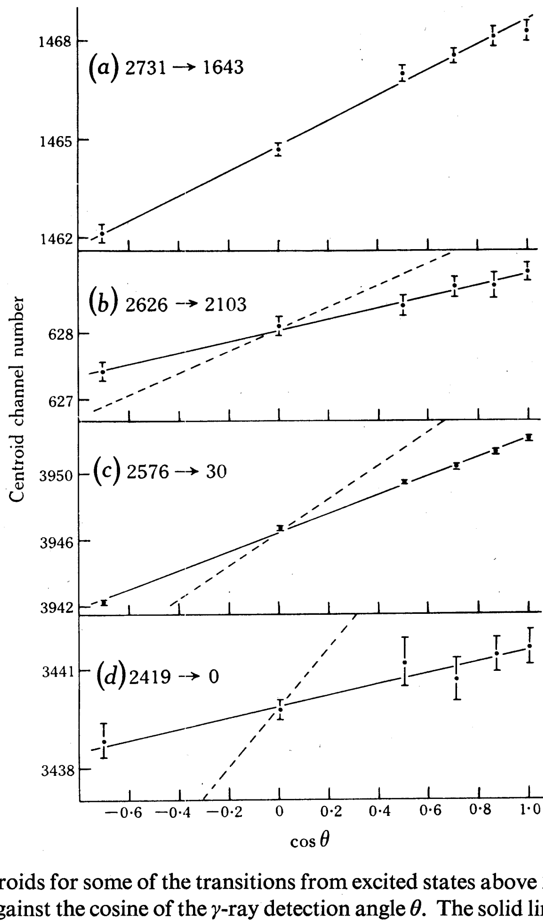

Fig. 4. Peak centroids for some of the transitions from excited states above 2400 keV excitation energy, plotted against the cosine of the γ-ray detection angle θ. The solid lines are least squares fits to the data, while the dashed lines indicate the maximum possible centroid shifts calculated from the kinematics. The 2731 → 1643 keV peak was fully shifted, and the dashed line indicating the maximum shift has been omitted for clarity. Note the small Doppler shift of the 2419 keV transition. This level decays via strongly inhibited M1 and E2 transitions to levels at 800 and 30 keV and the ground state.

For the angular distribution analysis, data were normalized using the areas of the 661 and 1613 keV full energy peaks produced in the decays of the zero-spin levels (Endt and van der Leun 1973) at 2122 keV in ^{40}Ar and 1643 keV in ^{40}K respectively. Agreement between the two normalizations was generally better than 3%. For the two highest energy runs at proton energies of 5·4 and 5·75 MeV, only the 661 keV peak was used for normalization, due to contamination of the 1613 keV peak with 1619 keV γ rays from the 2419 → 800 keV decay in ^{40}K.

The DSAM data were collected near threshold, so that all recoils of ^{40}K nuclei were confined to a narrow cone about the beam direction. It was assumed that the recoil velocity was equal to the centre-of-mass velocity (Warburton *et al.* 1967).

Results and Analysis

A typical spectrum observed at a proton bombarding energy of 5·75 MeV is shown in Fig. 2. Most of the peaks in the spectrum are produced by decays in ^{40}K, and these are the peaks that are labelled in Fig. 2 by their energies only. The major contaminants in the spectrum were γ rays produced by decays in copper, nickel and nitrogen as indicated, the nitrogen being a contaminant of the argon in the target cell.

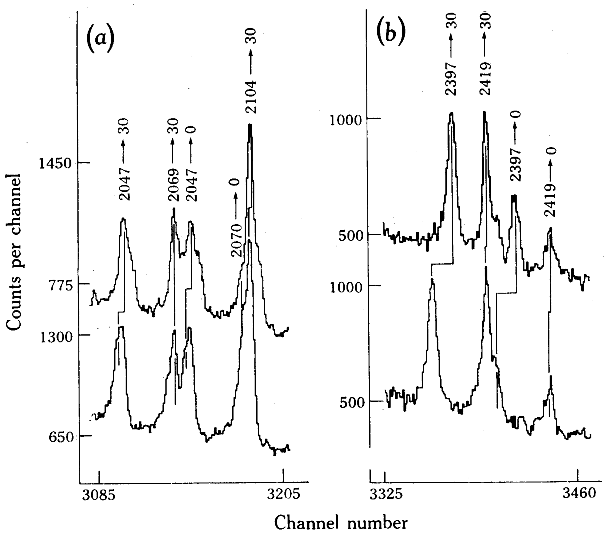

Fig. 5. Partial spectra illustrating observed Doppler shifts for the indicated levels in ^{40}K. The upper spectra of both (*a*) and (*b*) were accumulated at 0° and the lower at 135°. The 2419→0 keV transition was used to deduce the lifetime of the 2419 keV level, as it was the only peak produced by the decay of this level that was resolved at all angles. The lifetime of the 2069 keV level was deduced from the partially resolved doublet at approximately 2042 keV; the small Doppler shift of this level is evident.

Branching Ratios

Branching ratios were obtained by fitting a Legendre polynomial expansion (with even terms only) up to $P_4(\cos\theta)$ to the various angular distributions. The coefficient of $P_0(\cos\theta)$ when corrected for the photopeak efficiency of the detector was then taken as the relative intensity of the γ ray in question. Good agreement is obtained with values published by other authors (Twin *et al.* 1970; Wechsung *et al.* 1971; James *et al.* 1971; Davis *et al.* 1973; Endt and van der Leun 1973). Fig. 3 contains weighted averages of the available data on branching ratios of the levels below 2800 keV. The spin and parity assignments shown are a synthesis of the present and previous work (Wedberg and Segel 1973; Twin *et al.* 1970; Wechsung *et al.* 1971; James *et al.* 1971; Davis *et al.* 1973).

Lifetimes

The attenuated energy shift of the photopeak of each γ ray was obtained by the method of least squares from the dependence of the centroid channel number on $\cos\theta$, where θ is the γ ray detection angle relative to the proton beam direction. Fig. 4 shows some typical examples of these data. The experimentally determined centroids (points) are indicated together with the least squares fit (solid lines), while the dashed lines indicate the calculated full shifts expected from the kinematics. Spectra, typical of those from which the graphs of Fig. 4 were obtained, are illustrated in Fig. 5. If $\Delta C/\Delta\cos\theta$ is the gradient of a graph such as Fig. 4 then we have

$$F(\tau) = \frac{\Delta C/\Delta\cos\theta}{\beta(0)\,C_{90}},$$

where τ is the lifetime of the level, $\beta(0)$ is the heavy ion recoil velocity and C_{90} is the peak centroid. The uncertainty in $\beta(0)$ was evaluated in accordance with Appendix A of Warburton *et al.* (1967), and was typically 2%–10% of $\beta(0)$ for ^{40}K levels and 20% of $\beta(0)$ for ^{40}Ar levels. The statistical error in $\Delta C/\Delta\cos\theta$ was typically 5%; the errors due to the finite size of the detector were very small and were neglected in the analysis. Three levels (those at 2069, 2747 and 2808 keV in ^{40}K) were not represented in the spectra by resolved peaks, and in these cases $F(\tau)$ values were calculated from the observed centroid shift of the unresolved peak by estimating the ratio of the areas of the constituent peaks at each angle in the doublet of interest and using the $F(\tau)$ value of the other level concerned.

Table 1. Lifetimes of excited states in ^{40}Ar as determined in the present work

(1) E_i (keV)	(2) E_f (keV)	(3) $F(\tau)$	(4) τ (fs)
1461	0	14%±5%	1040^{+1160}_{-40}
2524	0	45%±8%	340±100
3209	1461	99%±10%	<30

Lifetimes were extracted from measured $F(\tau)$ values using the code DOPPLER (Bardin *et al.* 1971; A. D. W. Jones, personal communication). This code uses the expression for electronic stopping (Lindhard *et al.* 1963; Warburton *et al.* 1967)

$$(\mathrm{d}E/\mathrm{d}x)_{\mathrm{elec}} = K_e\, v/v_0\,,$$

where K_e can be calculated from equation (B5) of Warburton *et al.* (1967). However, we took the value of K_e to be 20% lower than this, namely $2\cdot46\ \mathrm{keV\,cm^2\,\mu g^{-1}}$. In the region of recoil velocities $v/v_0 < 0\cdot36$ (with $v_0 = c/137$), no experimental data exist against which to check the value K_e. Our value was chosen to lie within the probable error range of equation (B5) of Warburton *et al.* (estimated to be ±25%) and to give slightly better agreement with the well-known lifetimes of the low lying levels of ^{40}K; it increased the lifetimes by less than 10%. The method formulated by Blaugrund (1966) was used to evaluate nuclear stopping and scattering, while the density of solid argon used in the calculations was $1\cdot67\ \mathrm{g\,cm^{-3}}$, as given in Table 13 of Landolt-Bornstein (1967).

Table 2. Lifetimes, Legendre coefficients and mixing ratios for states in ^{40}K

(1) E_i (keV)	(2) E_f (keV)	(3) $F(\tau)$ (%)	(4) Present τ (fs)	(5) Previous τ (fs)	(6) Best τ (fs)	(7) a_2/a_0 (%)	(8) a_4/a_0 (%)	(9) E_{bom}[A] (MeV)	(10) $(J^\pi)_i$	(11) $(J^\pi)_f$	(12) Mixing ratio
800	30	40 ± 3	320 ± 30	420 ± 60	370 ± 50			3·26			
891	0	19 ± 3	1050 ± 200	1110 ± 150	1100 ± 120			4·74			
1959	30	24 ± 2	740 ± 40	960 ± 90	780 ± 60	-21 ± 1	-1 ± 1	4·74	2^+	3^-	$-0{\cdot}11\pm0{\cdot}03^B$
	800	25 ± 3				33 ± 1	1 ± 1			2^-	$0{\cdot}00\pm0{\cdot}05^B$
2047	30	36 ± 3	460 ± 30	540 ± 30	500 ± 30	-12 ± 2	-4 ± 2	4·74	2^-	3^-	$0{\cdot}00\pm0{\cdot}02,^B$ $-0{\cdot}09\pm0{\cdot}04$, 5·7
	800	35 ± 3				47 ± 3	3 ± 2			2^-	$-0{\cdot}05\pm0{\cdot}08,^B$ $-0{\cdot}66\pm0{\cdot}41$
2069	30	19 ± 4	1050^{+350}_{-210}	580 ± 80	620 ± 100			4·74			
2104	800	23 ± 3	840 ± 120	660 ± 130	760 ± 100	-22 ± 2	0 ± 3	4·74	1^-	2^-	$-0{\cdot}05,^B$ 0·53, 1, 4·3
2261	0	76 ± 4	100 ± 15	85 ± 10	90 ± 8	-5 ± 3	-4 ± 3	4·97	3^+	4^-	$0{\cdot}05\pm0{\cdot}06^B$
	30					44 ± 3	-3 ± 2			3^-	$-0{\cdot}01\pm0{\cdot}09^B$
2290	800	68 ± 4	135 ± 17	114 ± 15	124 ± 11	-5 ± 2	-1 ± 2	4·97	1^+	2^-	$-0{\cdot}14^B$
	1643	71 ± 5				-10 ± 1	5 ± 2			0^+	M1
2291	0	56 ± 5	224 ± 24	211 ± 14	215 ± 12	50 ± 3	-7 ± 4	5·03	{ 3^-	4^-	$0{\cdot}84^{+0{\cdot}49}_{-0{\cdot}34}$ [B,C]
	0								{ 4	4^-	$-0{\cdot}67\pm0{\cdot}3$, $-0{\cdot}02^{+0{\cdot}12}_{-0{\cdot}30}$ [C]
2397	0					19 ± 5	-8 ± 6	5·32	4	4^-	$+0{\cdot}32\pm0{\cdot}12$
	30	92 ± 7	<55	50 ± 20	50 ± 20	21 ± 3	-7 ± 3			3^-	$-0{\cdot}25\pm0{\cdot}04^C$
2419	0	19 ± 5	1060 ± 160	500^{+300}_{-150}	850 ± 200	6 ± 6	-13 ± 7	5·29	2^-	4^-	$-0{\cdot}17\pm0{\cdot}28$
	30					22 ± 3	3 ± 3			3^-	0·25, $2{\cdot}6^C$
	800					32 ± 3	-1 ± 2			2^-	$0{\cdot}03\pm0{\cdot}13,^C$ $-2{\cdot}2\pm0{\cdot}7^C$
2576	30	58 ± 2	224 ± 16	126 ± 34	200 ± 30	-13 ± 1	-1 ± 1	5·27	2^+	3^-	$-0{\cdot}03^{+0{\cdot}04}_{-0{\cdot}07},^C$ $7{\cdot}6^{+2{\cdot}0}_{-1{\cdot}3}$

2626	2104	52 ± 7				-1 ± 4	3 ± 4	5·44	0^-	1^-	M1
	800	43 ± 9	310 ± 54	343 ± 36	330 ± 30	-9 ± 14	21 ± 16			2^-	E2
2731	1643	98 ± 8	<40	<55	<40	-13 ± 4	-3 ± 5	5·44	1	0^+	M1 or E1
2747	0					12 ± 5	2 ± 5	5·44	2^-	4^-	$0\cdot00\pm0\cdot1^{C}$
	30	64 ± 4	177 ± 36	270^{+200}_{-120}	180 ± 30	30 ± 3	-1 ± 4			3^-	$0\cdot87^{+1\cdot6\ C}_{-0\cdot5}$
	0								3^-	4^-	$0\cdot19\pm0\cdot14,^{C}$ $3\cdot4^{+2\cdot9\ C}_{-1\cdot3}$
	30									3^-	$0\cdot18^{+0\cdot18\ C}_{-0\cdot11}$
2756	30					-2 ± 3	-11 ± 4	5·44	2	3^-	$0\cdot00\pm0\cdot12,^{C}$ $4\cdot7^{+14\cdot4}_{-2\cdot0}$
	800	98 ± 6	<35	<30	<30	38 ± 4	1 ± 4			2^-	$-0\cdot19^{+0\cdot26}_{-0\cdot19},^{C}$ $2\cdot1^{+0\cdot7\ C}_{-1\cdot3}$
	30								3^-	3^-	$-5\cdot1^{+2\cdot4}_{-6\cdot3},$ $0\cdot47^{+0\cdot23\ C}_{-0\cdot09}$
	800									2^-	$-0\cdot45\pm0\cdot11^{C}$
2785·6	0	100^{+0}_{-11}	<40		<40	-58 ± 13	-11 ± 4	5·44	3	4^-	$-19<\delta<-0\cdot09$
	0								4	4^-	$\delta<-4\cdot9$, $\delta>0\cdot81$
	0								5	4^-	$0\cdot19^{+0\cdot34}_{-0\cdot19},$ $1\cdot8\pm0\cdot4$
2786·2	30	91 ± 5	<55		<55	43 ± 2	-6 ± 2	5·44	2^-	3^-	$0\cdot81\pm0\cdot34$
	30								3	3^-	$-1\cdot1\pm0\cdot4$, $-0\cdot03\pm0\cdot14$
2808	800	57 ± 5	235 ± 60	140 ± 90	206 ± 40						

[A] E_{bom} is the bombarding energy, with the energy loss in the target entrance foil subtracted. Where data for the two energies have been averaged, the quoted value is a weighted mean.

[B] Mixing ratio is in agreement with that determined by Twin *et al.* (1970).

[C] Mixing ratio is in agreement with that determined by Davis *et al.* (1973).

Lifetime information obtained in the present experiments for ^{40}Ar and ^{40}K is given in Tables 1 and 2 respectively. In both tables, columns 1 and 2 specify the transition of interest, and columns 3 and 4 list the value of $F(\tau)$ obtained in the present analysis together with the derived mean lifetime. The value of $F(\tau)$ is found to be quite insensitive to the actual bombarding energy. In addition, Table 2 lists the error-weighted mean lifetime obtained from previous data (Wechsung *et al.* 1971; Wedberg and Segel 1973; James *et al.* 1971) in column 5 and the overall error-weighted mean, or best value, in column 6. The lifetime values do not include any contribution from uncertainties in the stopping theory (estimated to be $\pm 25\%$).

Angular Distribution Analysis for ^{40}K

The angular distribution analysis benefits greatly if the data are taken near threshold, due to the predominantly s-wave nature of the emitted neutrons. Twin *et al.* (1970) have estimated that, if the bombarding energy is within 100 keV of threshold, the p-wave transmission coefficient is less than 10% of that of the s-wave. Hence the excited level substate population was limited to $m_z = 0$ and ± 1, where m_z is the projection of the level spin onto the quantization axis; all higher spin projection substates were assumed to be unpopulated. (Possible population of the $m_z = \pm 2$ substates was also tested; see discussion in following subsections.) No further model-dependent assumptions were made to restrict the population parameter solutions.

In ^{40}K, few of the decays are to spin-zero levels, and consequently it was necessary to consider the variation of the mixing ratios of up to three transitions originating from the same level. This was done by fitting simultaneously the angular distributions of all resolved primary γ rays produced by the decay of a level. A program was written which grid searched over the possible mixing ratios δ_i. For each transition, the quantity $x_i = \arctan \delta_i$ was varied in 5° steps between 90° and $-90°$. For each set of mixing ratios $(\delta_1, \delta_2, ...)$, a linear least squares analysis fixed the population parameters of the decaying level, and the best fitting angular distributions and associated χ^2 values were computed. Examination of these χ^2 values, using two-parameter contour plots or single parameter plots, enabled solutions to be found. The $0{\cdot}1\%$ confidence level was adopted as the criterion for a mixing ratio solution, and the quoted errors indicate the possible variation in mixing ratio within this criterion. For each level, the validity of the assumption that only the two substates of lowest m_z were populated was tested by repeating the fit, allowing a 10% population of the $m_z = \pm 2$ substate. In most cases the mixing ratio results were unchanged, but cases where there was a significant difference are discussed specifically in the following subsections.

Table 2 summarizes the Legendre coefficients a_2/a_0 and a_4/a_0 of the angular distributions obtained at the different bombarding energies E_{bom} considered in the analysis (columns 7, 8 and 9). Comparison of Table 2 with the results of Twin *et al.* (1970), Wechsung *et al.* (1971) and Davis *et al.* (1973) indicates that there is little variation of these coefficients with bombarding energy. Table 2 also lists spin–parity assignments for the excited levels of ^{40}K and the mixing ratios obtained in the above analysis (columns 10, 11 and 12), the sign convention being that of Rose and Brink (1967). The criteria adopted for acceptable transition strengths are those formulated by van der Leun (1972). Before briefly discussing the data for each level, we present the results obtained for the 2261 keV level as an example of our analysis methods.

2261 keV Level

From analysis of the angular distribution to the ground state and the 30 keV first-excited state, we obtained possible spins of 1, 2 or 3 for the 2261 keV level. Spin 1 implies an octupole transition to the $J^{\pi} = 4^{-}$ ground state. Most favourably this would be an E3 transition but, from the adopted lifetime of 90 ± 8 fs and the branching ratios (see Fig. 3), the width would be $(11 \pm 1) \times 10^{4}$ W.u. (Weisskopf units; Wilkinson 1960). This value is far too large and therefore $J = 1$ can be ruled out.

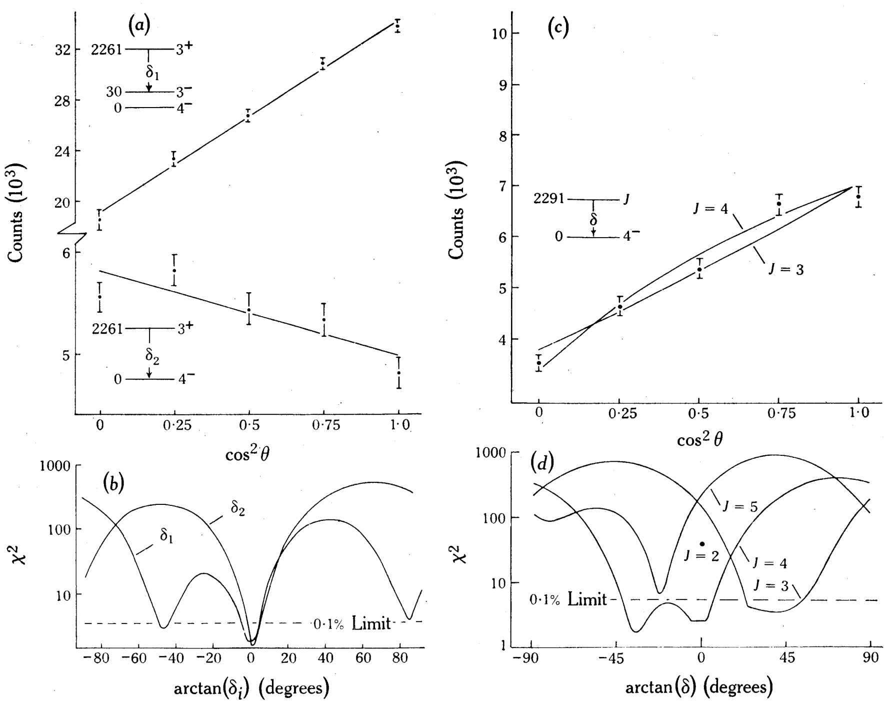

Fig. 6. Plots of: (*a*) and (*c*), Gamma-ray angular distributions for the indicated transitions (energies in keV); (*b*) and (*d*), χ^2 versus mixing ratio, showing sections through contour plots, labelled with the mixing ratio being varied. In (*a*), $J = 3$ is the only allowed spin for the 2261 keV level (see text), and the least squares fits (straight lines) are for this case only. In (*c*), the least squares fits (curves) are for the indicated J values and for mixing ratios corresponding to the minima of the χ^2 plots in (*d*). Spins $J = 2$ and 5 did not give acceptable fits to the data at the $0 \cdot 1$% confidence limit.

For $J = 2$ the smallest value of $\delta(2261 \rightarrow 0)$ is $|\delta| = 0 \cdot 15$, implying an E3 width of 2500 W.u., so that $J = 2$ is not a possible spin either. Hence we obtain $J = 3$, in agreement with the statistical compound-nucleus-dependent assignments of Twin *et al.* (1970) and Wechsung *et al.* (1971). The linear polarization of the 2231 keV γ ray measured by Twin *et al.* fixes the parity as even. We can therefore discard our mixing ratio solutions $\delta(2261 \rightarrow 30) = -1 \cdot 0 \pm 0 \cdot 1$ and $\delta(2261 \rightarrow 0) = 7 \cdot 6 \pm 2 \cdot 0$, as they imply M2 widths of 310 ± 30 and 120 ± 12 W.u. respectively. The remaining values, consistent with dipole transitions in each case, agree well with previous results (Twin *et al.*; Wechsung *et al.*). The above restrictions and results are unaffected by a 10% population of the $m_z = \pm 2$ substates. Figs 6*a* and 6*b* illustrate the results we obtained for this level: $J^\pi = 3^+$, $\delta_1 = -0{\cdot}01 \pm 0{\cdot}09$ and $\delta_2 = 0{\cdot}05 \pm 0{\cdot}06$. Our lifetime of 100 ± 15 fs is in good agreement with the previous best value.

1959 keV Level

Spin values of other than 2 have been rigorously rejected by analysis of the angular distributions produced by the two decays from the 1959 keV level. The mixing ratio solutions for $J = 2$ agree well with other results (Twin *et al.* 1970; Wechsung *et al.* 1971). Consistent values of $F(\tau)$ were obtained from these data as shown in Table 2. Our value for the lifetime is in reasonable agreement with the previous best value.

2047 keV Level

Spin values of 1, 2 and 3 were obtained for the 2047 keV level by analysis of the data. Twin *et al.* (1970), using the reaction-dependent compound nuclear analysis, were able to eliminate $J = 1$ and 3. For $J = 2$ the solutions for the mixing ratios obtained by us are in reasonable agreement with those quoted by Twin *et al.* We also obtained other solutions. Good agreement exists between quoted lifetimes for this level (see Table 1 of Wedberg and Segel 1973), and our value tends to favour the result of Wedberg and Segel.

2069 keV Level

No angular distribution analysis was performed for the 2069 keV level, as it produced no resolved γ-ray peaks in our spectra. Doppler shift analysis was performed (using the partially resolved peaks due to the decays $2047 \rightarrow 0$ and $2069 \rightarrow 30$ keV) on spectra accumulated at a bombarding energy 130 keV above threshold. The resulting lifetime of 1050^{+350}_{-210} fs is longer than those in the literature (Wedberg and Segel 1973), which are in poor agreement.

2104 keV Level

Only the decay of the 2104 to the 800 keV level was sufficiently resolved in our spectra to permit angular distribution analysis. Spin possibilities of 1, 2 or 3 were obtained from this analysis. The level is assumed to be the spin 1^- member of the $\pi \mathrm{d}_{3/2}^{-1}\, \nu \mathrm{p}_{3/2}$ configuration in the literature, although this has not been proved rigorously (see e.g. Twin *et al.* 1970). Our result for $J = 1$ (see Table 2) limits δ to three ranges of value, none of which can be eliminated by consideration of the lifetime of this level. A considerable spread of lifetimes has been published (see Table 1 of Wedberg and Segel 1973). Our value is in good agreement with the mean of these.

2290 keV Doublet

In agreement with Twin *et al.* (1970) and Davis *et al.* (1973), we associate γ-ray decays to the ground state and the levels at 800 and 1643 keV with two levels: a level at 2290 keV decaying to the 800 and 1643 keV states, and a level at 2291 keV which decays to the ground state. We discuss these two levels separately below.

2290 keV Level

The present data from the two decays of the 2290 keV level restrict the spin to $J = 1$. However, our data, accumulated at an average bombarding energy 250 keV above threshold, do not restrict the value of the mixing ratio for the transition to the 800 keV level (due to insufficient alignment of the 2290 keV level). Davis *et al.* (1973), using the statistical compound nucleus model, quote a value of $\delta(2290\rightarrow 800) = 0\cdot 02\pm 0\cdot 05$, which is in reasonable accord with the result of Wechsung *et al.* (1971). These values are consistent with the even-parity assignment made to this level by Twin *et al.* (1970). Our lifetime of 135 ± 17 fs is in excellent agreement with the results of Wechsung *et al.* (1971) and James *et al.* (1971).

2291 keV Level

Figs 6*c* and 6*d* illustrate that $J = 3$ or 4 are the only possible spins for the 2291 keV level, while transition strength arguments rule out $J^{\pi} = 3^{+}$. Except for the mixing ratio $\delta(2291\rightarrow 0)$ for $J = 4$ measured by Twin *et al.* (1970), all published mixing ratios (Twin *et al.* 1970; Wechsung *et al.* 1971; Davis *et al.* 1973) and lifetimes (Twin *et al.*; Wechsung *et al.*; Wedberg and Segel 1973) for this level are in complete accord with each other and this work. Our spin–parity assignment of $J^{\pi} = 3^{-}$ or $4^{\pm}$ for this level agrees with the model-dependent assignments of Twin *et al.*, Wechsung *et al.*, and Davis *et al.*

2397 keV Level

Simultaneous angular distribution analysis of our data for the two decays of the 2397 keV level to the ground and the 30 keV level limits the spin to $J = 2$, 3 or 4. The lifetime limit of <55 fs is consistent with the previously accepted value quoted in Table 2. Transition strength arguments rule out all even-parity assignments. Our data therefore restrict the level spin and parity to 2^{-}, 3^{-} or 4^{-}. Davis *et al.* (1973), using the statistical compound nucleus model, have restricted the level spin–parity to $J^{\pi} = 4^{-}$. For this spin assignment, the mixing ratios determined by us and quoted by Davis *et al.* (1973) are in good agreement for the transition to the 30 keV level but not for the transition to the ground state.

2419 keV Level

Simultaneous analysis of the three angular distributions from the 2419 keV level, which were accumulated at an average proton bombarding energy 470 keV above threshold, limit the spin to 1, 2 or 3. Transition strength arguments rule out $J^{\pi} = 1^{\pm}$ and 2^{+}, and hence $J^{\pi} = 2^{-}$ or $3^{\pm}$ are obtained from the present analysis. Davis *et al.* (1973) have rejected $J = 3$ for this level from an analysis using the statistical compound nucleus model of the decay to the level at 800 keV. Agreement between their mixing ratios and ours is good. The lifetime of this level was obtained from analysis of the Doppler shift of the ground state transition. This measurement was more precise than those previously made (Wechsung *et al.* 1971; James *et al.* 1971; Wedberg and Segel 1973) and favoured a longer lifetime than had previously been accepted.

2576 keV Level

Spins 1–4 were obtained from analysis of the single decay of the 2576 keV level to the state at 30 keV. Twin *et al.* (1970) and Davis *et al.* (1973) managed to limit the spin to 2 or 4 by utilizing the compound nucleus model for the reaction. Good agreement is apparent between their mixing ratios and those obtained in our analysis, except that for spin 2 we obtain a further possible solution (see Table 2). For $J = 4$ the parity must be odd; an M2 width of 2·1 W.u. results from an even-parity assignment. However, Fink and Schiffer (1974) have found $l_n = 2$ for this level, which implies even parity. Hence we reject $J = 4$ and assign $J^\pi = 2^+$. Our lifetime result for this level is in excellent agreement with all published values except that of Wechsung *et al.* (1971).

2626 keV Level

The isotropic nature of both decays from the 2626 keV level allows spin assignments of $J = 0$, 1 or 2. That both decays are isotropic suggests that spin zero is most likely. If this is so then this level should probably be identified with the $\pi\, d_{3/2}^{-1}\, \nu\, p_{3/2}$, $J^\pi = 0^-$ shell-model state predicted in this region. This identification is also consistent with the $l = 1$ stripping result of Fink and Schiffer (1974). If $J = 0$ the parity must be odd, as the transition to the second-excited state is too fast to be M2 (Γ(M2) = 172±16 W.u.). The lifetime of 310±54 fs measured in our experiments is in excellent agreement with published data (Wechsung *et al.* 1971; James *et al.* 1971; Wedberg and Segel 1973).

2731 keV Level

Angular distribution analysis of the decay of the 2731 keV level to the 0^+ state at 1643 keV fixed the spin of this level uniquely as $J = 1$, in agreement with James *et al.* (1971) and Davis *et al.* (1973). We have been able to improve on the upper limit to the lifetime for this level, which is now <40 fs.

2747 keV Level

Analysis of the two major decays of the 2747 keV level permits spin values of 2, 3 or 4. Transition strength arguments rule out $J^\pi = 2^+$ and 4^+, while stripping results (Fink and Schiffer 1974) indicate that the parity is odd. We therefore assign $J^\pi = 2^-$ or 3^-. This conclusion agrees with that of Davis *et al.* (1973), and agreement between the two sets of mixing ratios is good except for the $J = 3\,\delta(2747 \rightarrow 30)$ ratio. Our value for the lifetime of this level is in reasonable accord with that published by James *et al.* (1971) but is considerably more precise.

2756 keV Level

Simultaneous analysis of the decays of the 2756 keV level to those at 30 and 800 keV restrict the possible level spins to 1, 2 or 3. Transition strength arguments eliminate $J = 1^+$ and 3^+; hence we obtain $J^\pi = 1^-$, 2 or 3^-. Davis *et al.* (1973), using the statistical compound nucleus model, have limited the spin to 2 or 3^-. Agreement is quite good between their mixing ratios and ours, although we obtained more possibilities (see Table 2).

2786 keV Doublet

Davis *et al.* (1973) have established the existence of a doublet at 2786 keV. In our spectra, obtained at a proton bombarding energy 240 keV above threshold, we see γ rays from transitions to levels at 30 keV, 1959 keV and ground. The γ-ray peak from the transition to the level at 1959 keV is contaminated with a γ ray produced in ^{60}Ni of the same energy, and is unsuitable for analysis. We measured the energy of the level which decays to the 30 keV level to be $2786 \cdot 2 \pm 0 \cdot 5$ keV. Angular distribution analysis of the transition led to possible spins $J = 1$, 2 or 3. Also, using this transition, we measured the lifetime as <55 fs. Transition strength arguments rule out $J^\pi = 1^\pm$ and 2^+, and hence we have $J^\pi = 2^-$ or 3, in agreement with Davis *et al.* (1973) who have limited the spin to 3. We measured the energy of the level decaying to ground to be $2785 \cdot 6 \pm 0 \cdot 8$ keV, which disagrees by 2 keV with the measurement of Davis *et al.* (1973). Angular distribution analysis of this transition, assuming it is from one level only, limited the spin to 2–5, while transition width arguments rule out $J = 2$.

Discussion

The present work has established the utility of a solid argon target for nuclear structure experiments, and the conditions whereby a uniform target with a reproducible and known density is formed have been established. The technique has recently (Southon *et al.* 1976; Radford *et al.* 1978) been used to determine several previously unknown lifetimes in ^{40}Ar and to investigate excited state lifetimes in ^{41}Ar. The lifetimes measured in the present work in Ar have already been discussed (Southon *et al.* 1976). No further comment on these is necessary. Although in most cases the lifetimes measured for ^{40}K in the present work have been previously reported, they provide a valuable independent assessment of these mean lives using an unusual, and rather light, stopping material. They also supersede the preliminary values reported by Poletti and Beale (1972). Within the limitations of the DSAM method, lifetimes (or limits) of all levels in ^{40}K below 2810 keV are now reasonably well established except for the 2069, 2419 and (possibly) the 2576 keV levels.

The value of the essentially model-independent angular correlation analysis used in the present work lies in the generally excellent agreement between the appropriate mixing ratio solution obtained by us and the statistical-model-dependent solutions obtained by previous workers (Twin *et al.* 1970; Davis *et al.* 1973). Of the 24 cases where comparison is readily possible, 19 mixing ratios are in excellent agreement, while only 2 cases of direct conflict were found: between the present work (also that of Davis *et al.*) and that of Twin *et al.* for the 2291 keV to ground-state transition for $J_i = 4$, and between the present work and that of Davis *et al.* (1973) for the 2397 keV to ground-state transition. In the former case, it would appear that the value obtained by Twin *et al.* (1970) is in error. No reason can be given for the second discrepancy.

Recently Thomas *et al.* (1974) presented extensive results of shell model calculations of M1 and E2 transition strengths in ^{40}K. We can add nothing further to these calculations. We do, however, wish to comment on two simple calculations of level and configuration energies in the nucleus. The use of large shell-model computer codes has in recent years revolutionized our ability to calculate nuclear spectroscopic properties. But the dividends do not come entirely without cost; it is extremely difficult to obtain any reasonable physical insight as to why the particular results turn up as they do. In ^{40}K, because of its proximity to the closed shell nucleus ^{40}Ca, it is still possible to carry out simple calculations on the odd-parity states which do illuminate the physics of the problem. In the following subsections, we give the results of a simple weak coupling calculation which enables us to predict the approximate relative excitation energies of the (p–h) and the (3p–3h) configurations. In addition, a simple δ-force calculation together with an application of the Pandya transformation enables us to predict the positions of the different states composing the (p–h) configurations.

Weak Coupling Calculation

The weak coupling model (Bansal and French 1964; Bernstein 1972) has recently (Kolata *et al.* 1976) been used with some success in an attempt to understand the configurations giving rise to the yrast levels of nuclei in the mass region $35 \leqslant A \leqslant 39$. A summary of the application of this model to a calculation of the energies of the lowest configurations arising from (p–h) and (3p–3h) excitations is given in Table 3.

Table 3. Weak coupling (1p–1h) and (3p–3h) energies in ^{40}K

Configuration	E_{theor} (MeV)	E_{expt} (MeV)	Configuration	E_{theor} (MeV)
$d_{3/2}^{-1} f_{7/2}$	0·31	0·44	^{37}Ar(4·99)*^{43}Sc(0·0)	2·87
$d_{3/2}^{-1} p_{3/2}$	2·39	2·10	^{37}K(0·0)*^{43}Ca(0·0)	4·06
$s_{1/2}^{-1} f_{7/2}$	2·84	2·46	^{37}Cl(0·00)*^{43}Ti(0·0)	3·92
$s_{1/2}^{-1} p_{3/2}$	4·91	?		

Of course, the model neglects the effect of the residual interactions which will split the energies of the states with different spin for each configuration. The first point to note, however, is the accuracy with which the average energies of the three lowest (p–h) configurations are predicted. Obviously, too, the states arising from the $s_{1/2}^{-1} p_{3/2}$ configuration will not occur until nearly 5 MeV excitation. The lowest (3p–3h) excitation is predicted at 2·87 MeV, and it arises from the coupling of the holes to $t = 3/2^-$ and the particles to $t = 1/2$. We would therefore expect to see the first states arising from this configuration at approximately 2·87 MeV. Indeed the lowest lying odd-parity states which have significant (3p–3h) components in large shell-model calculations can be identified with the states at 2291 and 2419 keV.

Simple Shell Model Calculation

Expressions have been given by de Shalit (1953) for the interaction energy in a configuration arising from the coupling of two unlike particles. Writing the interaction energy as $\Delta E(j_p j_n J)$ in terms of radial harmonic oscillator functions defined for instance by Elliot and Lane (1957) and following de Shalit and Feshbach (1974) we obtain

$$\Delta E(j_p\, j_n\, J) = (2j_p+1)(2j_n+1)(8\pi)^{-1}\left(\int_0^\infty r^2\, R^2_{n_p l_p}(r)\, R^2_{n_n l_n}(r)\,\mathrm{d}r\right) F(J)\,, \qquad (1)$$

where

$$F(J) = \begin{pmatrix} j_p & j_n & J \\ \frac{1}{2} & -\frac{1}{2} & 0 \end{pmatrix}^2 \left\{ V_s\left(\frac{1+(-)^{l_p+l_n+J}}{2}\right) + V_t\left(\frac{1-(-)^{l_p+l_n+J}}{2} + \frac{\{2j_p+1+(-)^{j_p+j_n+J}(2j_n+1)\}^2}{4J(J+1)}\right)\right\}.$$

The interaction energies of the particle–hole states are simply obtained using the Pandya transformation (de Shalit and Feshbach 1974)

$$\Delta E(j_p^{-1} j_n J) = -\sum_{J'} (2J'+1) \begin{pmatrix} j_p & j_n & J \\ j_p & j_n & J' \end{pmatrix} \Delta E(j_p j_n J') .$$

The singlet and triplet interaction strengths $V_s I_{df}$ and $V_t I_{df}$, where I is the radial integral contained within parentheses in equation (1), can be fixed by comparing the calculated energies with the energies of the $d_{3/2} f_{7/2}$ quartet in ^{38}Cl. Their values are then $-5 \cdot 69$ and $-11 \cdot 28$ MeV respectively. Apart from the single-particle and single-hole energies, this then fixes the only two adjustable parameters in the calculation. Evaluation of the radial integrals gives

$$I_{df} : I_{dp} : I_{sf} : I_{sp} = 1 \cdot 00 : 0 \cdot 672 : 0 \cdot 682 : 1 \cdot 377 ,$$

with

$$E(2p_{3/2}) - E(1f_{7/2}) = 2 \cdot 08 \quad \text{MeV} \qquad \text{and} \qquad E(2s_{1/2}^{-1}) - E(1d_{3/2}^{-1}) = 2 \cdot 52 \quad \text{MeV} .$$

Table 4. Particle–hole states in ^{40}K using a δ function residual interaction

Configuration	J	E_{theor} (MeV)	E_{expt} (MeV)	Configuration	J	E_{theor} (MeV)	E_{expt} (MeV)
$d_{3/2}^{-1} f_{7/2}$	2	0·90	0·80	$d_{3/2}^{-1} p_{3/2}$	0	2·73	2·63
	3	0·34	0·03		1	2·40	2·10
	4	0·00	0·00		2	2·00	2·05
	5	0·91	0·89		3	2·52	2·07 +(?)
$s_{1/2}^{-1} f_{7/2}$	3	2·90	2·07 +(2·80+3·26)	$s_{1/2}^{-1} p_{3/2}$	1	5·68	
	4	2·72	2·40		2	5·27	

The results of the calculation are given in Table 4, where it can be seen that quite reasonable agreement between theory and experiment has been achieved. The apparent discrepancy between the calculated and predicted energy of the second $J^\pi = 3^-$ state can be traced to the experimental fact (Enge *et al.* 1959; Betts *et al.* 1975) that this state contains both $1d_{3/2}^{-1} 1p_{3/2}$ and $2s_{1/2}^{-1} 1f_{7/2}$ components. The relatively low-lying odd-parity states at 2291 and 2419 keV, since they cannot arise from the (1p–1h) configuration, must be principally (3p–3h), as predicted by Thomas *et al.* (1974).

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