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1973 J. Phys. A: Math. Nucl. Gen. 6 1030

(http://iopscience.iop.org/0301-0015/6/7/022)

J. Phys. A: Math., Nucl. Gen., Vol. 6, July 1973. Printed in Great Britain.

A proposed $K^\pi = 0^-$ band in ^{44}Sc

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Received 5 March 1973

Abstract. The lifetimes and spins of the low-lying negative parity states of ^{44}Sc have been determined. The spin sequence 1^-, 2^-, 3^-, 4^- and possibly 0^- assigned to the 68, 235, 425, 631 and 146 keV states, together with the measured transition strengths, suggest that these states are members of a $K^\pi = 0^-$ band based upon a $d_{3/2}$ hole configuration.

Rotational bands based on the low-lying $d_{3/2}$ proton–hole configuration are well known in the odd-A Sc isotopes (Maurenzig 1971) and similar bands with $K^\pi = 0^-$ and 3^- are expected in the odd–odd nucleus ^{44}Sc. The proposed $K = 0$ band explains the low-lying negative parity states which are not expected in a shell model framework and, as will be shown, provides a consistent explanation for the previously inexplicable properties of the isomeric states at 68 and 146 keV.

Since the $\pi(d_{3/2})^{-1}$ configuration cannot be directly identified in ^{44}Sc by proton pick-up reactions, these states must be identified from their γ decay. Many low-lying states of positive and negative parity are known (Manthuruthil and Prosser 1972) from particle reactions, but only the γ decays of the 68 and 146 keV states have been extensively studied. Although previously thought to have positive parity, a remeasurement (Simpson *et al* 1969) of the mass of ^{44}Ti has shown that negative parity is possible for both of these states. A level scheme deduced from the ^{43}Ca(p, γ)^{44}Sc reaction has been reported (Poirier and Manthuruthil 1971), however many of the low energy transitions which characterize the decay of the negative parity states were not observed.

We have established the energies and decay modes of states up to about 2 MeV in ^{44}Sc from a study of the ^{44}Ca(p, nγ)^{44}Sc ($Q = -4{\cdot}429$ MeV) and ^{41}K(α, nγ)^{44}Sc reactions, using the Liverpool EN tandem and an escape-suppressed spectrometer. States in ^{44}Sc were identified from their γ decay, consistent with their observed threshold in the (p, n) reaction. These assignments were confirmed by γ–γ coincidence measurements following the ^{41}K(α, n) reaction. The angular distributions of strong γ rays from states populated near threshold in the (p, n) reaction were measured. These distributions were fitted with the use of population parameters predicted from a Hauser–Feshbach calculation (Sheldon and Van Patter 1966), and the formalism of Rose and Brink (1967), to determine spins and mixing ratios. Thick target measurements and the appropriate analyses were made at a number of energies between 80 and 700 keV above threshold for each state, and for a range of optical model parameters. Lifetime measurements were made using the Doppler shift attenuation method with the ^{41}K(α, nγ) reaction at 6·5 and 7·5 MeV, and the recoil distance method with the ^{28}Si(^{18}O, pnγ) reaction at 31 MeV. A full discussion of these measurements will be reported elsewhere, the present discussion being limited to transitions involving the low-lying negative parity states.

The results for these states are given in figure 1, together with the measured spins and lifetimes. As an example of the analysis, the distributions and χ^2 fits for the three transitions from the 425 keV state, which is believed to have negative parity (Ohnuma

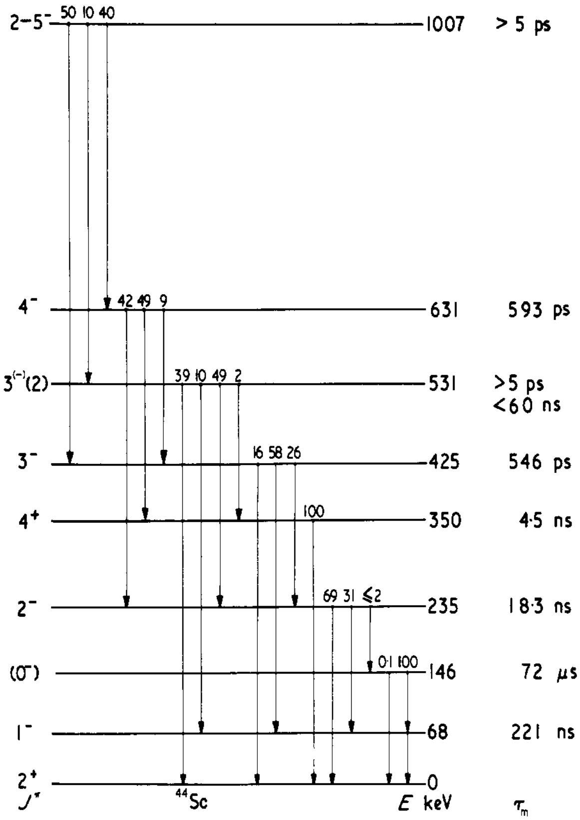

Figure 1. Partial decay scheme of ^{44}Sc showing the transitions involving the low-lying negative parity states. The errors on the branching ratios and lifetimes are included in table 1.

and Sourkes 1971, Manthuruthil and Prosser 1972, and references therein), are shown in figure 2. These data are only consistent with a spin of 3 for this level, and the fit to the 425 to 68 keV transition determines the spin of the 68 keV level as 1. Further, the lifetime of the 425 keV state eliminates an M2 possibility for this transition, and fixes the parity of the 68 keV state as negative. The data and fits for the strong transitions from the negative parity 235 keV state are shown in figure 3. The fits are only consistent with a spin of 2 for this state. Figure 4 shows the results for the negative parity 631 keV state. The fits are acceptable for $J = 4$ and for $J = 2$ or 3. However, a spin of 3 requires a strong M2 admixture in the E1 transition to the 351 keV 4^+ state. From the lifetime of this state, this M2 would amount to about 560 Wu, therefore the spin 3 can be discounted. Similarly, the spin 2 alternative requires a very strong M2 transition with a large E3 admixture and this can also be discounted. Therefore the 631 keV state has a spin of 4.

The results are summarized in table 1. The determinations of the mixing ratios for the $2^- \rightarrow 1^-$ and $3^- \rightarrow 2^-$ transitions are ambiguous although the $\delta = 3{\cdot}3$ solution for

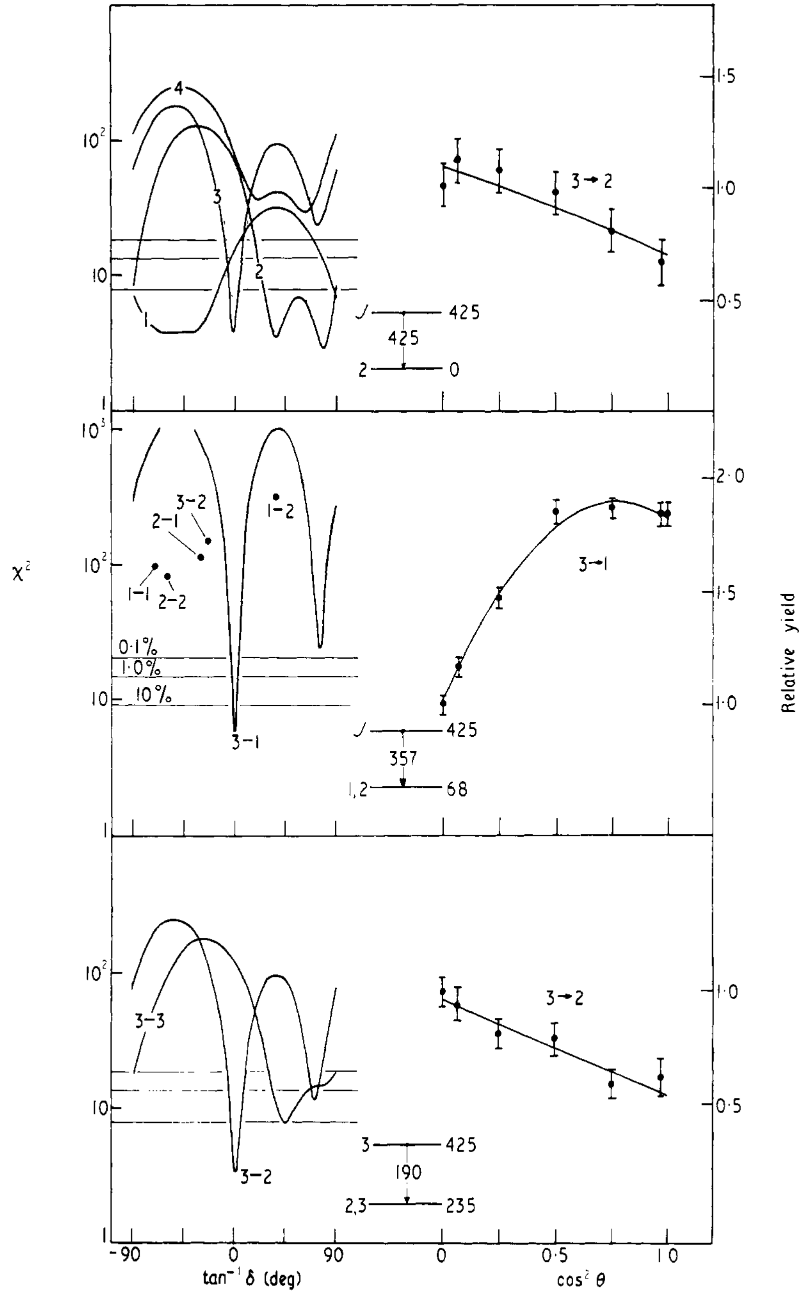

Figure 2. The angular distributions and χ^2 fits of the three transitions from the 425 keV state in ^{44}Sc, from the ^{44}Ca(p, n) reaction at 5·15 MeV. The full points on the χ^2 plot are minima of the fits for those spin values over the full range of δ.

the $3^- \rightarrow 2^-$ transition requires an E2 admixture of 155 Wu and this is unlikely. The assignments of 1^-, 2^-, 3^- and 4^- to the states at 68, 235, 425 and 631 keV suggest that they may be interpreted as members of the expected $K^\pi = 0^-$ band. The 531 keV level may be the first member of the $K^\pi = 3^-$ band. These identifications are supported by

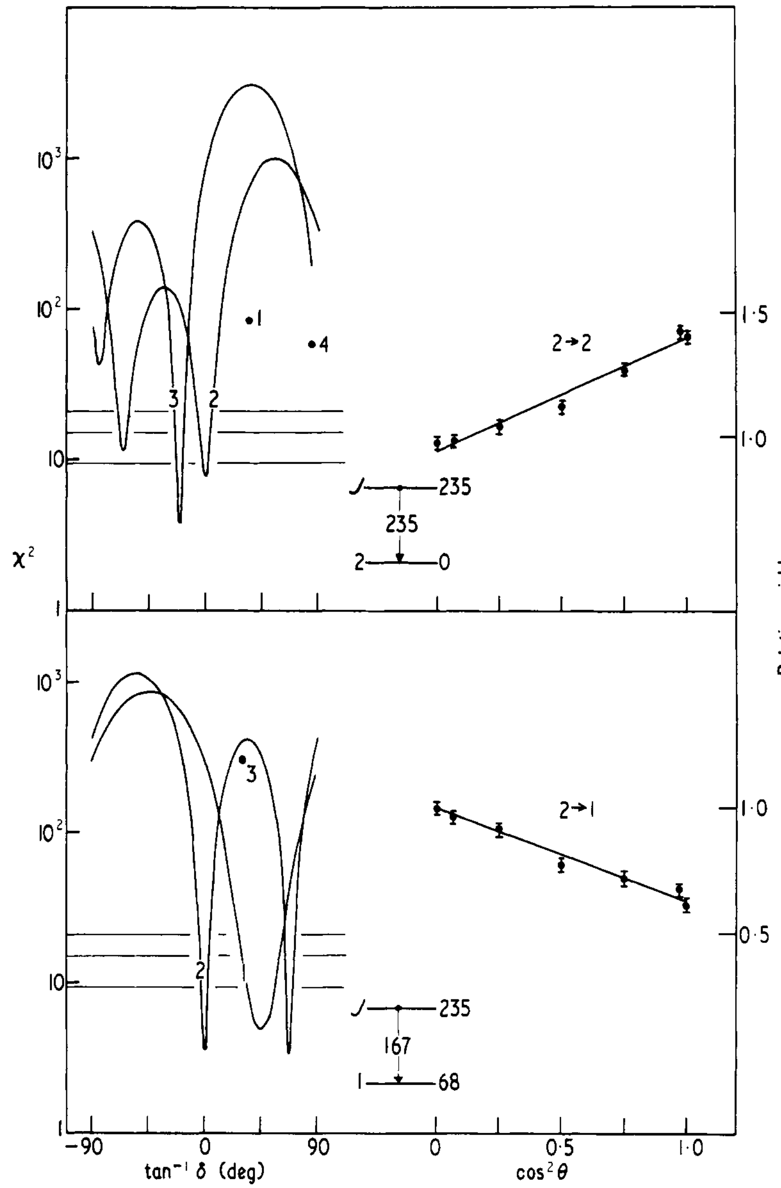

Figure 3. The γ ray angular distributions and fits to the transitions from the 235 keV state from the ^{44}Ca(p, n) reaction at 5·15 MeV.

the γ decays which are in agreement with those expected for a $K = 0$ band in an odd–odd nucleus (Gallagher 1960, Varshalovich and Peker 1961). In particular the enhanced E2 crossover transitions confirm the collective character of the states. The pure M1 stopover transitions are expected since $\Delta J = 1$ E2 transitions in a $K = 0$ band are forbidden. The model would not favour the $\delta = 2{\cdot}5$ solution for the mixing ratio of the $2^- \to 1^-$ transition. The retardation of the M1 transitions implies approximate equality of the particle gyromagnetic ratios since the M1 transition probability is proportional to $(g_{\Omega_p} - g_{\Omega_n})$. The retardation of the E1 transitions ($\sim 5 \times 10^{-6}$ Wu) is in agreement with

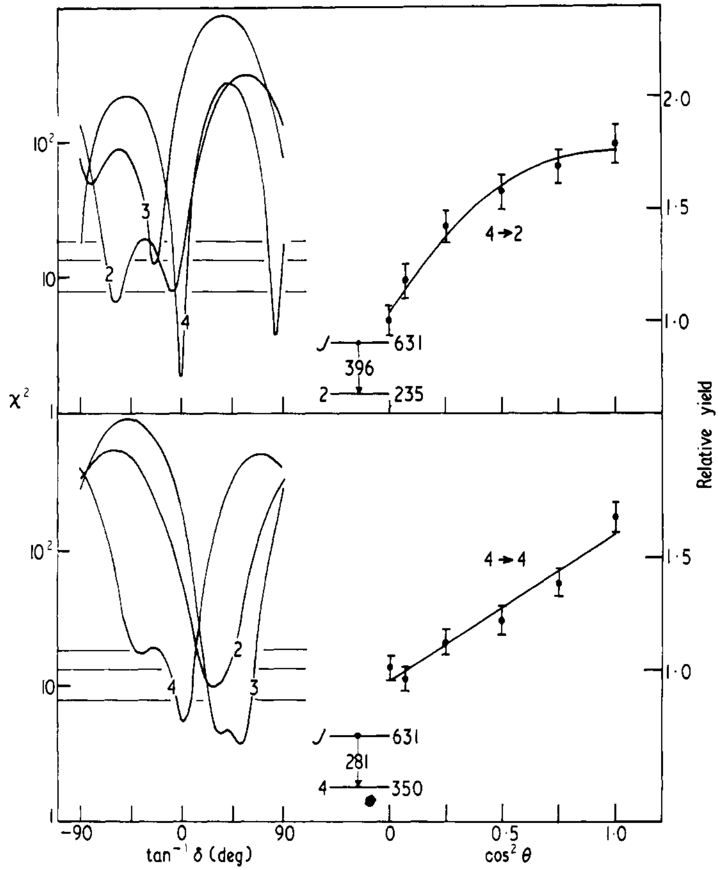

Figure 4. The distributions and fits to the transitions from the 631 keV state in ^{44}Sc from the ^{44}Ca(p, n) reaction at 5·75 MeV.

similar transitions from $d_{3/2}$ proton–hole states in the neighbouring nuclei. Finally, in a $K = 0$ band the magnetic moment is proportional to the collective gyromagnetic ratio g_R which is approximately $+0{\cdot}4$ for this nucleus (Greiner 1966). This is in agreement with the observed g factor of $+0{\cdot}342$ for the 68 keV 1^- state (Ristinen and Sunyar 1967).

The 1^- assignment to the 68 keV state, together with previous information (Ristinen and Sunyar 1967, Glass and Kliwer 1968) on the 146 keV state, now limits the spin of the 146 keV level to 0 or 1. The $J^\pi = 0^-$ possibility is most consistent with the data. In particular, the measured γ–γ correlation for the $146 \rightarrow 68 \rightarrow 0$ keV cascade is in excellent agreement with a $0^- \rightarrow 1^- \rightarrow 2^+$ spin sequence with pure M1 and E1 transitions.

If this state does have $J^\pi = 0^-$ then it may be identified as the $K^\pi = 0^-$ intrinsic state. The M2 strength of the 0·1 % branch to the ground state from the 146 keV level would be about 10^{-3} Wu. This again is consistent with the hindered M2 transitions from $d_{3/2}$ hole states in neighbouring nuclei (Holland *et al* 1964). The $146 \rightarrow 68$ keV M1 transition is a factor of 100 more retarded than the other M1 transitions within the band.

It is noted that the 0^- state is above the 1^- state and that, in the case of a simple $K = 0$ band in an odd–odd nucleus, the even and odd spin members are expected to

Table 1. Transition strengths for the low-lying negative parity states in ^{44}Sc

Level (keV)	J^π	τ_m	Decay to keV, J^π, (%)	Mixing ratio δ	Transition strengths (Wu) E1	M1	E2
68	1^-	221 ± 3 ns[a]	$0, 2^+, 100$		$(11{\cdot}2\pm0{\cdot}2)\times10^{-6}$		
$234{\cdot}6\pm0{\cdot}2$	2^-	$18{\cdot}3\pm3{\cdot}2$ ns	$0, 2^+, 69\pm2$	$0{\cdot}00\pm0{\cdot}05$	$(2{\cdot}3\pm0{\cdot}4)\times10^{-6}$		
			$68, 1^-, 31\pm2$	$-0{\cdot}02\pm0{\cdot}02$		$(1{\cdot}2\pm0{\cdot}2)\times10^{-4}$	$<0{\cdot}04$
				or		or	or
				$2{\cdot}50\pm0{\cdot}2$		$(1{\cdot}6\pm0{\cdot}4)\times10^{-5}$	10 ± 2
$424{\cdot}7\pm0{\cdot}3$	3^-	546 ± 60 ps	$0, 2^+, 16\pm2$	$-0{\cdot}03\pm0{\cdot}06$	$(3{\cdot}0\pm0{\cdot}3)\times10^{-6}$		
			$68, 1^-, 58\pm2$	$0{\cdot}00\pm0{\cdot}03$			$16{\cdot}2\pm1{\cdot}8$
			$235, 2^-, 26\pm2$	$0{\cdot}02\pm0{\cdot}06$		$(22\pm2)\times10^{-4}$	$<3{\cdot}4$
				or		or	or
				$3{\cdot}3^{+1{\cdot}4}_{-0{\cdot}8}$		$(1{\cdot}9\pm1{\cdot}0)\times10^{-4}$	155 ± 28
$531{\cdot}3\pm0{\cdot}3$	$[3^-]$	$5\text{ ps} < \tau < 60\text{ ns}$	$0, 2^+, 39\pm2$	$0{\cdot}04\pm0{\cdot}03$	$3\times10^{-8} < \|M\|^2 < 2\times10^{-4}$		
			$68, 1^-, 10\pm1$	$-0{\cdot}02\pm0{\cdot}07$			$0{\cdot}01 < \|M\|^2 < 41$
			$235, 2^-, 49\pm2$	$0{\cdot}02\pm0{\cdot}03$		$10^{-5} < \|M\|^2 < 6\times10^{-2}$	
			$350, 4^+, 2\pm1$		$4{\cdot}4\times10^{-8} < \|M\|^2 < 2{\cdot}6\times10^{-4}$		
$630{\cdot}8\pm0{\cdot}2$	4^-	593 ± 43 ps	$235, 2^-, 42\pm2$	$-0{\cdot}02\pm0{\cdot}03$			$6{\cdot}4\pm0{\cdot}5$
			$350, 4^+, 49\pm2$	$+0{\cdot}02\pm0{\cdot}09$	$(30{\cdot}0\pm2{\cdot}0)\times10^{-6}$		
			$425, 3^-, 9\pm1$	not fitted		$(5{\cdot}5\pm0{\cdot}5)\times10^{-4}$	

a From Ristinen and Sunyar (1967).

separate in energy because of the residual p–n interaction. The level ordering is not simple, however, and probably indicates some mixing from other states. This mixing may be from the expected $K^\pi = 1^-$ or 2^- bands based on the $s_{1/2}$ proton–hole state, and in this case the 0^- state would remain pure. Such mixing might explain the level ordering and the difference in M1 strength of the 0^- state.

In conclusion, the spins and lifetimes of the low-lying negative parity states of ^{44}Sc have been determined and these states are identified from their γ decay as members of the expected $K^\pi = 0^-$ band based on the $d_{3/2}$ proton–hole state. The 68 and 146 keV states, whose properties to date have been unexplained, are identified as the 1^- and possibly the 0^- members of this band.

We thank Professor L L Green and Drs J F Sharpey-Schafer and A N James for the use of facilities at Liverpool.

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