The γ decay of low-lying states in ^{44}Sc (populated in $^{44}Ca(p,n\gamma)$, $^{41}K(\alpha,n\gamma)$ and $^{28}Si(^{18}O,pn\gamma)$ reaction)

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The γ decay of low-lying states in ^{44}Sc

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Abstract. Levels in ^{44}Sc have been studied using the reactions $^{44}Ca(p, n\gamma)^{44}Sc$, $^{41}K(\alpha, n\gamma)^{44}Sc$ and $^{28}Si(^{18}O, pn\gamma)^{44}Sc$. The level scheme up to 1·5 MeV has been established. Lifetimes have been measured using the Doppler shift attenuation method and the recoil distance method. γ ray angular distributions were measured near threshold in the (p, n) reaction and these results together with the lifetimes and branching ratios allow spin assignments to be made for most of the states. The low-lying negative parity states are interpreted as deformed bands, co-existing with the spherical positive parity states predicted by the shell model.

1. Introduction

The odd–odd nucleus ^{44}Sc has been extensively studied using a variety of particle reactions. These have included the compound nucleus reactions $^{44}Ca(p, n)^{44}Sc$ (McMurray *et al* 1967) and $^{41}K(\alpha, n)^{44}Sc$ (Smith and Steigert 1961) as well as the direct charge exchange reaction $^{44}Ca(^3He, t)^{44}Sc$ (Manthuruthil and Prosser 1972). The neutron pick-up reactions $^{45}Sc(p, d)^{44}Sc$, $^{45}Sc(^3He, \alpha)^{44}Sc$ and $^{45}Sc(d, t)^{44}Sc$ have also been studied (Kashy 1964, Rapaport *et al* 1971, Ohnuma and Sourkes 1971) as has the proton stripping reaction $^{43}Ca(^3He, d)^{44}Sc$ (Schwartz 1968). Schlegel *et al* (1970) have reported the two-particle transfer reaction $^{42}Ca(^3He, p)^{44}Sc$ and several groups have studied the $^{46}Ti(d, \alpha)^{44}Sc$ reaction (Bjerregaard *et al* 1964, Guichard *et al* 1972, Wallen and Hintz 1972).

Despite the wide scope of these experiments the level scheme is not well established and few reliable spin assignments have been made. This is due, in part to the high level density in ^{44}Sc and the consequent difficulty of resolving the particle groups, and in part to the low cross section for exciting many of the low-lying states in the direct reactions. It is expected that some of these weakly excited states would have substantial proton hole strength. These of course cannot be directly identified because ^{45}Ti is unstable.

Only the γ decays of the 68 and 146 keV isomeric states, which are populated in the $^{44}Ti(EC)^{44}Sc$ decay, have been extensively studied (Bergstrom and Thieberger 1962, Kliwer *et al* 1963, Ristinen and Sunyar 1967, Glass and Kliwer (1968) but the configurations of these states have not been understood. A preliminary study of the $^{43}Ca(p, \gamma)^{44}Sc$ reaction has been reported (Poirier and Manthuruthil 1971).

The purpose of the present study was to establish the energies, decay modes, lifetimes and spins of the low-lying states in ^{44}Sc. With this information it was hoped

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that the configurations of the low-lying states would be explained. As previously reported (Dracoulis *et al* 1973b) the results allow the identification of the low-lying negative parity states as members of a $K^\pi = 0^-$ band, and further details of those results will be presented here.

The levels of ^{44}Sc and their γ ray decay modes were established using the ^{44}Ca(p, nγ) and ^{41}K(α, nγ) reactions. These measurements are described in § 2, and the established level scheme of ^{44}Sc is compared with previous experimental information in § 3. The lifetimes of many of the states were determined using the Doppler shift attenuation method (DSAM) and the recoil distance method (RDM). These measurements are presented in § 4. In order to limit the spins of the observed states in ^{44}Sc γ ray angular distributions were measured with the residual nuclei aligned by population near threshold in the ^{44}Ca(p, n)^{44}Sc reaction. The results and analysis are described in § 5. The properties of the 68 and 146 keV isomeric states are discussed in detail in § 6 and a general discussion of the low-lying levels in ^{44}Sc is given in § 7.

2. The ^{44}Sc level scheme

2.1. The ^{44}Ca(p, n)^{44}Sc reaction

The Liverpool escape-suppressed spectrometer (Sharpey-Schafer *et al* 1971) was used to detect the low energy γ rays from a thick $CaCO_3$ target (enriched to 97 % in ^{44}Ca) which was bombarded with protons from the Liverpool EN tandem accelerator. Transitions in ^{44}Sc were identified by increasing the beam energy in discrete steps from below threshold for the ^{44}Ca(p, n)^{44}Sc, ($Q = -4{\cdot}42$ MeV) reaction up to a proton energy of 6·8 MeV which corresponds to a maximum excitation energy of 2·2 MeV. By observing the threshold energy for the production of particular γ rays, and using accurate energy summations and relative intensities, transitions could be assigned to particular states in ^{44}Sc. Comparison measurements were made with natural $CaCO_3$, CaO and evaporated metallic Ca targets to identify possible contaminant γ rays. A γ ray spectrum, taken at a proton energy of 6·0 MeV, is illustrated in figure 1.

A search was also made for an expected low energy transition from the 235 to 146 keV state. Because of the low energy a small volume Ge(Li) counter with a thin Be window was used with a thin-walled chamber. The counter, which was placed at 125° to the beam direction, viewed the front of a metallic ^{44}Ca target which was bombarded with 5·3 MeV protons. A weak 88 keV transition was observed but in the absence of any coincidence information this transition has been included in the decay scheme with an upper limit on the branching ratio corresponding to the observed intensity.

Particular care was taken to determine the relative Ge(Li) detection efficiencies in each experimental arrangement to correct properly for the absorption of the low energy γ rays.

2.2. The ^{41}K(α, n)^{44}Sc reaction

Singles γ rays from the ^{41}K(α, n)^{44}Sc ($Q = -3{\cdot}39$ MeV) reaction were observed in the bombardment of gold backed 400 µg cm^{-2} KI targets, enriched to 96 % in ^{41}K, with α particle beams of energies between 4·5 and 10 MeV. Because of the Coulomb barrier it was not possible to populate the ^{44}Sc states at threshold and the ^{44}Sc γ rays were identified by comparing the spectra with those obtained in the (p, n) study. These

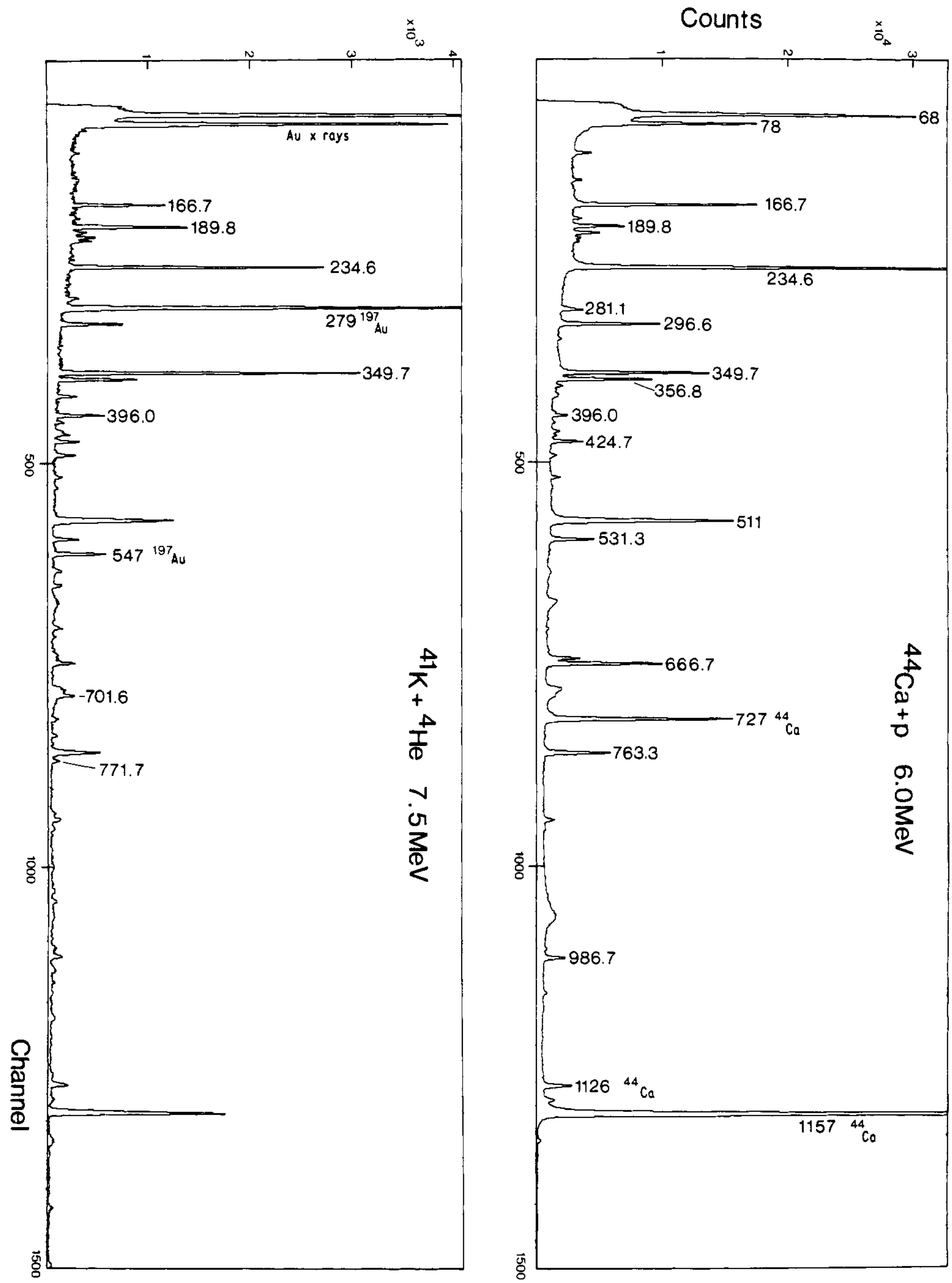

Figure 1. The low energy portions of the γ ray singles spectra following: (*a*) the $^{44}Ca(p, n\gamma)^{44}Sc$ reaction at 6·0 MeV with a $CaCO_3$ target; and (*b*) the $^{41}K(\alpha, n\gamma)^{44}Sc$ reaction at 7·5 MeV with a KI target on a gold backing. The energies of the γ rays in keV are indicated on the figure. The spectra were recorded with the Liverpool escape-suppressed spectrometer.

results provided an independent check on the transition assignments and branching ratios. A spectrum is included in figure 1. It is apparent that the relative population of particular states in ^{44}Sc differs in the two reactions. In order to confirm the decay scheme γ–γ coincidences were measured using a thick KI target pressed on to a tantalum mesh bombarded with a 10 MeV α particle beam from the Manchester HILAC. Two Ge(Li) detectors with active volumes of 36 cm^3 and 45 cm^3 were placed at right angles to the beam direction on opposite sides of the target about 3 cm apart. The three-parameter data, consisting of two linear signals from the γ ray detectors and a time difference signal, were analysed using three 4096 channel ADC's and a PDP9 computer. The data were recorded in an event by event mode on magnetic tape. Coincidences were established by setting windows on the time spectrum (FWHM of 50 ns) and on the γ rays of interest. Background and random events were estimated by setting windows on a featureless part of the spectrum above the γ ray of interest, and on the random spectrum in the time window. Several spectra with backgrounds subtracted are illustrated in figure 2. The coincidence data are summarized in table 1. Singles γ ray spectra were also recorded for comparison with those taken under the different experimental conditions described above and in § 2.1.

A level scheme for ^{44}Sc, consistent with the results of all the present measurements is shown in figure 3. The branching ratios include the results of the angular distribution measurements which will be described later. Although the excitation functions in the (p, n) reaction extend to a proton bombarding energy which corresponds to an excitation of 2·2 MeV in ^{44}Sc, only states up to 1·43 MeV are included in the decay scheme. A number of γ rays which could be attributed to the decay of higher states, many of which are known from the particle reactions, were observed, however in the absence of coincidence information and because of the increasing complexity of the spectra at higher energies, these were not reliably assigned.

3. Comparison with previous schemes

All of the levels assigned in the present work can be identified with levels observed in the particle transfer studies providing allowance is made for the expected energy discrepancies. Another level scheme has recently been proposed by Poirier and Manthuruthil (1971) from a study of the ^{43}Ca(p, γ)^{44}Sc reaction. The levels assigned by those authors are for the most part in agreement with those seen in the present study, particularly for states populated by primary transitions in the (p, γ) study. However, there are several discrepancies in the levels assigned and a large number of discrepancies in the decays.

For example, the level at 745 keV was assigned from the (p, γ) work with decays to ground and by a 397 keV transition to the 350 keV state. A 745 keV transition was observed but in coincidence with the 763 keV (ground state) transition. Further, the 396 keV transition was assigned, from the coincidence data, as feeding the 235 keV state.

Poirier and Manthuruthil assigned a level at 1106 keV as decaying by a 100% 464 keV transitions to a state at 642 keV. The present (p, n) threshold data assign the 464 keV γ ray as the 531 → 68 keV transition. This γ ray was observed below threshold for a 1106 keV state. Further there was no evidence for a level at 642 keV which, according to Poirier and Manthuruthil, decays by a 100% 496 keV transition to the 146 keV state. This γ ray was not observed in any of the present reactions.

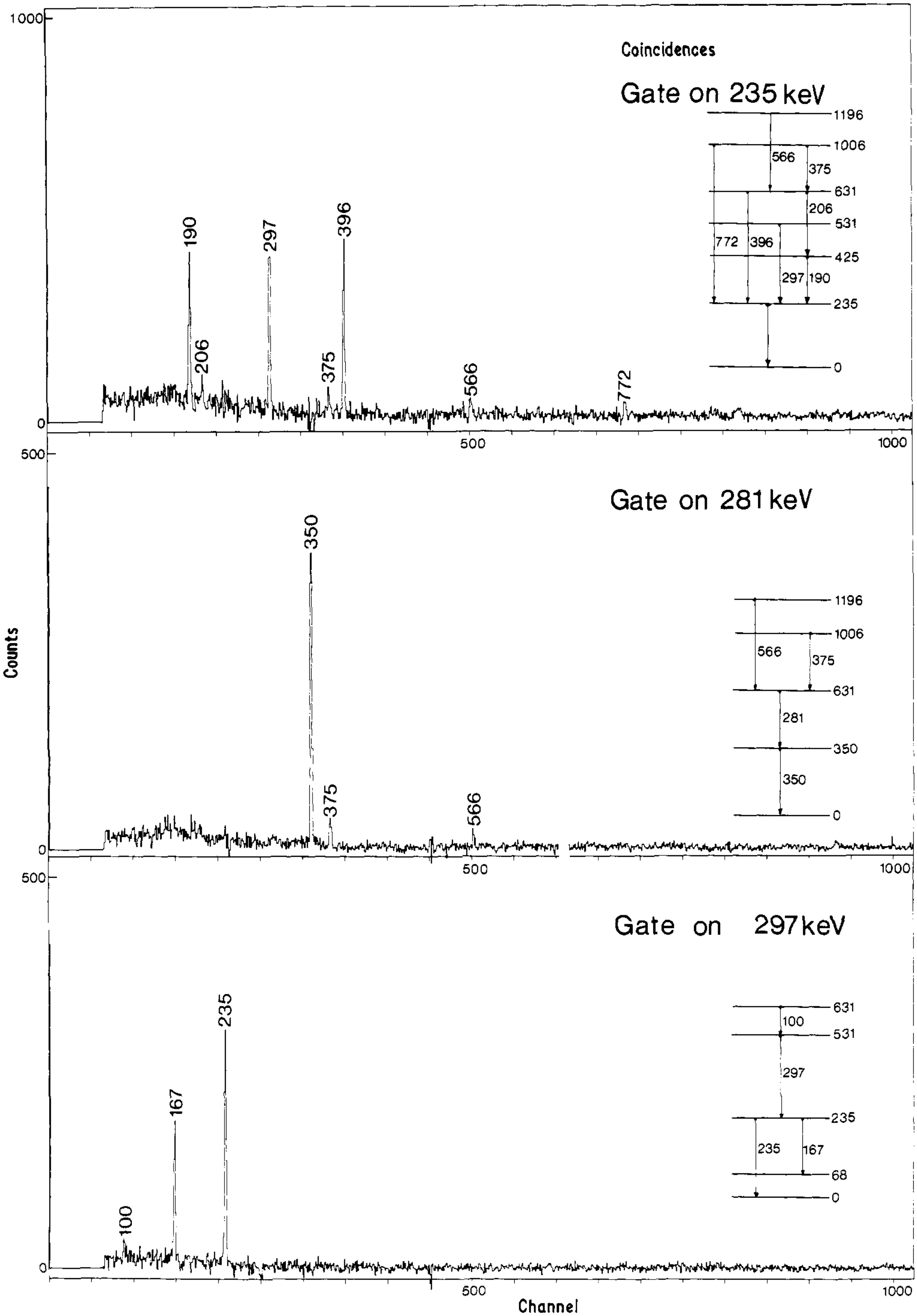

Figure 2. Examples of the γ–γ coincidence spectra obtained following the $^{41}K(\alpha, n\gamma)^{44}Sc$ reaction. From top to bottom the spectra shown are in coincidence with the 235, 281, and 297 keV γ-rays. The background due to Compton scattered γ rays in the coincidence gate has been subtracted in each case. The energies of those γ rays which appear clearly in each window are marked on the figure. A partial level scheme, showing the relationship of the gating γ ray to the γ rays observed to be in coincidence with it, is shown on the right of each spectrum.

Table 1. γ–γ coincidences in ^{44}Sc from the $^{41}K(\alpha, n\gamma)^{44}Sc$ reaction. The energies are in keV

Window	Coincident γ rays
167	190, 297, 375, 566
190	167, 206, 235, 375, 566, 582, 1002
206	190, 357, 425
235	190, 206, 297, 375, 396, 566, 772, (927), (1052)
281	350, 375, 566, (1052)
297	100, 167, 235
350	181, 281, 375, 566, 657, 702, 836, 976, (1052)
357	206, 582, 772, 1002
375	281, 396
396	167, 235, 281, 350, 375, (1052)
425	206, 582, 772
531	—
582	190, 357, 425
667	(762)
702	350
763	745, 830
772	167, 190, 235, 357, 425
1002	190, 357
1052	281, (350), 396
1186	—

As a final example, a state at 1426 keV was assigned in the (p, γ) work and in the present study but with substantially different transitions. Poirier and Manthuruthil assigned transitions to ground, to the 1106 keV state, the 763 keV state and the 350 keV state. Of these only the ground state transition was observed here, and from the threshold and coincidence data transitions to the 68 keV, possibly the 146 keV, the 235 keV and the 425 keV states were assigned.

Similar discrepancies occur for a number of other level assignments and transitions. Further, γ rays below about 200 keV were not reported by Poirier and Manthuruthil and these, from the present study comprise the main branches from the low-lying states.

4. Lifetime measurements

4.1. Doppler shift attenuation method

The centroid shifts of γ rays from the $^{41}K(\alpha, n)^{44}Sc$ reaction were measured as a function of angle using the Liverpool escape-suppressed spectrometer. The targets, which were placed at 45° to the beam direction, were as described in § 2.2. γ ray spectra were recorded at five angles (taken in random order) between 0° and 125° to the beam direction and at beam energies of 6·5 and 7·5 MeV. The experimental attenuation factors $F(\tau)$ were extracted from a linear fit to the peak centroids as a function of the cosine of the angle. It was assumed that the angular distribution of the emitted neutrons was symmetrical about 90° and therefore that the recoiling nuclei move in the beam direction with the velocity of the centre of mass. This is a reasonable approximation in an endothermic reaction at low energies (Schwarzschild and Warburton 1968). The theoretical $F(\tau)$ curve was calculated using the formalism of Blaugrund (1966) and the stopping power theory of Lindhard *et al* (1963).

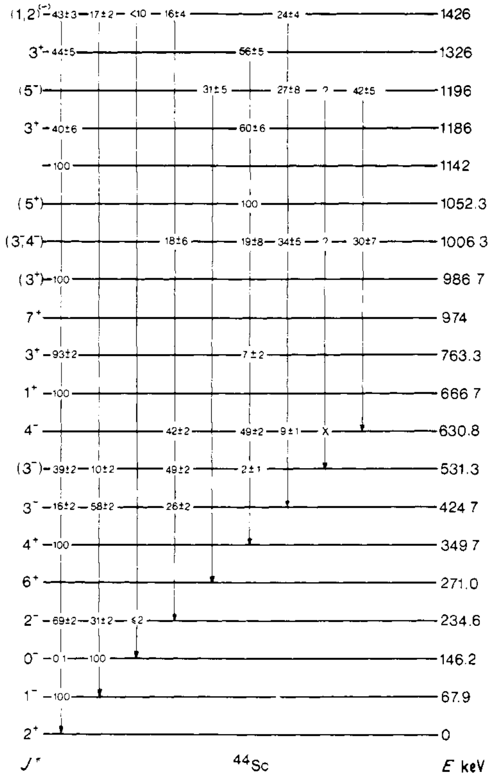

Figure 3. The level scheme of ^{44}Sc showing the γ decays and measured branching ratios of the observed levels in ^{44}Sc. The branching ratios shown for the 68 and 146 keV states are taken from Ristinen and Sunyar (1967). The level energies are given in keV on the right and the adopted spins and parities on the left. The assignments of the spins and parities are discussed in the text (§ 5 and 6).

Several of the measured centroids, plotted as a function of cos θ, are illustrated in figure 4 together with the linear fits. The final lifetimes are included in table 2. The errors on the lifetimes are statistical. There is a further 25 % error in the time scale due to uncertainties in the stopping power theory.

4.2. Recoil distance measurements

Targets of natural Si, evaporated to 250 μg cm^{-2} on 2 mg cm^{-2} stretched gold foils were irradiated with 31 MeV ^{18}O ions from the Liverpool EN tandem accelerator. This energy was found to be the peak, relative to the competing channels, for the ^{28}Si(^{18}O, pnγ)^{44}Sc reaction. The targets were mounted with the gold backing facing the beam to minimize the energy loss of the recoiling Sc nuclei. The calculated energy of the ^{18}O beam after passing through the gold was 26·3 MeV. This agreed well with the observed Doppler shift of the γ rays when account was taken of the energy loss of the recoils in the target.

A standard 'plunger' (Alexander and Bell 1970) arrangement with a gold stopper mounted on a precision micrometer was used. This included provision for adjusting the stopper face to be parallel to the target surface and a charge measuring system for the

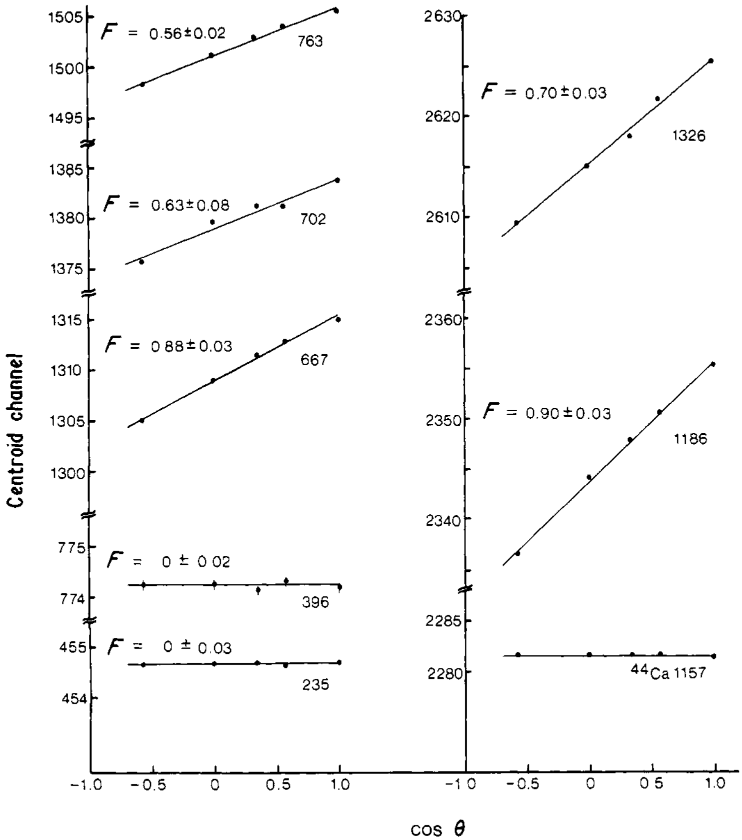

Figure 4. The position (channel number) of the centroid of the γ ray peak plotted as a function of the cosine of θ, the angle between the γ ray spectrometer and the beam direction, for some of the γ rays observed in the $^{41}K(\alpha, n\gamma)^{44}Sc$ reaction. In each case the full line shows the results of a least-squares fit to the data. The γ ray energies in keV and the resulting attenuation factors F are shown on the figure. The velocity of the recoiling nucleus is 0·55 % of the velocity of light. The change in the ordinate scales should be noted.

measurement of distances less than a few mil (1 mil = 0·001 in). A 41 cm^3 Ge(Li) detector placed at 0° to the beam direction detected γ rays for a range of stopper–target separations. Since the recoil velocity in this reaction was 1·97 % of the velocity of light the Doppler shifted γ rays, that is those decaying in flight, were well resolved from the unshifted γ rays from nuclei at rest in the stopper. Appropriate corrections were made to the observed intensities for the effects of the finite detector size, for the change in detection efficiency between the shifted and unshifted γ rays, for the difference in effective solid angle between those nuclei decaying in flight and those decaying in the stopper, and for the effect of the motion of the recoiling nuclei. For this last correction it was necessary to know the initial γ ray angular distribution and this was measured using a ^{28}Si target evaporated on a thick gold backing. These various corrections have been discussed in detail by Jones *et al* (1969) and by Diamond *et al* (1972). No correction was made for the effect of the attenuation of the γ ray angular distribution by the hyperfine fields due to the charge of the recoiling ion since these fields are not known for the Sc nuclei. If the fields are of the same order as those measured in heavier nuclei (Ashery *et al* 1967, Ben Zvi

Table 2. The measured lifetimes of states in ^{44}Sc. The attenuation factors $F(\tau)$ and lifetimes from the ^{41}K (α, nγ) ^{44}Sc reaction at 7·5 MeV are listed (DSAM) together with the results of the recoil distance measurements (RDM) from the ^{28}Si(^{18}O, pnγ) reaction. The upper limits of less than 50 ns are from the γ–γ coincidence measurements

Level energy (keV)	γ ray energy (keV)	DSAM $F(\tau)$ $v/c = 0{\cdot}55\,\%$	DSAM $\tau \pm 25\,\%$† (ps)	RDM lifetimes (ns)
234·6 ± 0·2	235	<0·06	>5·5	18·3 ± 3·2
349·7 ± 0·2	350	<0·04	>8	4·5 ± 0·4
424·7 ± 0·3	357	<0·04	>8	0·546 ± 0·060
531·3 ± 0·3	531	<0·02	>5·5	<50
	297	<0·06		
630·8 ± 0·2	396	<0·06	>5·5	0·593 ± 0·043
666·7 ± 0·4	667	0·88 ± 0·03	$0{\cdot}07^{-0{\cdot}02}_{+0{\cdot}014}$	
763·3 ± 0·4	763	0·56 ± 0·02	0·31 ± 0·02	
986·7 ± 0·4	987	0·15 ± 0·04	$2{\cdot}0^{-0{\cdot}5}_{+0{\cdot}9}$	
1006·3 ± 0·4	582	⩽0·04	⩾8	<50
1052·3 ± 0·4	702	0·63 ± 0·08	$0{\cdot}24^{-0{\cdot}06}_{+0{\cdot}08}$	
1185·8 ± 0·6	1186	0·90 ± 0·03	0·056 ± 0·016	
1196 ± 1	566	<0·1	>3	<50
1326 ± 1	1326	0·70 ± 0·03	0·18 ± 0·02	

† The systematic error of ±25 % is due to uncertainties in the stopping power theory.

et al 1968) the corrections are negligible for the long lifetimes measured in the present work. Finally, no correction was made for the effect of feeding from higher states since the relative intensities of the observed feeding transitions are small.

The γ rays from the 235, 350, 425 and 631 keV long-lived states were analysed. As an example the results for the 397 keV γ ray from the 631 keV state, and the 357 keV γ ray from the 425 keV state are illustrated in figure 5. The 357 keV transition has been corrected for the intensity of the shifted component of the longer lived 350 keV state. The data are shown as a semi-logarithmic plot of the unshifted intensity as a function of the target–stopper separation. The gradient of the least-squares fit is the ratio $1/\bar{v}\tau$ where $\bar{v}$ is the average recoil velocity which was determined from the γ ray energies as 1·97 ± 0·02 % of the velocity of light and τ is the mean lifetime.

Although the states at 531, 1006 and 1196 keV have lifetimes which were too long for DSAM measurements, their lifetimes were not measured in the (^{18}O, pn) reaction because they were only weakly excited. The final lifetimes are listed in table 2 and include upper limits on the 531, 1006 and 1196 keV lifetimes estimated from the γ–γ coincidence measurements.

5. γ ray angular distributions

5.1. Angular distribution measurements

The angular distributions of the strong γ rays from each state were measured at a number of proton energies. γ ray spectra were recorded at angles of 0°, 30°, 45°, 60°, 75°, 90° and in some cases 10° relative to the incoming beam direction. The Liverpool

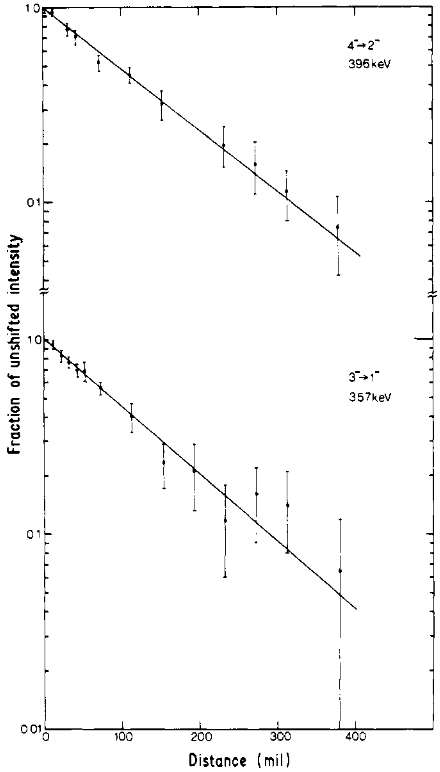

Figure 5. A semi-logarithmic plot of the fraction of the unshifted intensity against the target–stopper distance (in mil) for the 396 keV ($4^- \rightarrow 2^-$, 631 → 235 keV) and 357 keV ($3^- \rightarrow 1^-$, 425 → 68 keV) γ rays emitted following the $^{28}Si(^{18}O, np\gamma)^{44}Sc$ reaction. The full lines show the results of least-squares fits to the data. The measurements and the corrections applied to the data are discussed in the text (§ 4.2).

escape-suppressed spectrometer was used to detect the γ rays. The targets were thick $CaCO_3$ pellets enriched to 97 % in ^{44}Ca, mounted at 45° to the incoming beam direction. The yield of the isotropic 728 keV 0_2^+ to 2^+ transition in ^{44}Ca which arises from the $^{44}Ca(p, p')^{44}Ca$ reaction was used to normalize the spectra at each angle. The activity spectra confirmed that this ^{44}Ca state is not populated in the $^{44}Sc(\beta)^{44}Ca$ decay.

5.2. Efficiency measurements

Because many of the transitions in ^{44}Sc are of low energy, particular care was taken in the determination of the corrections for the Ge(Li) relative efficiencies, the chamber anisotropies and for attenuation of γ rays in the target. Efficiency measurements were made with standard sources of ^{133}Ba, ^{125}Sb, ^{152}Eu and ^{56}Co which covered an energy range of 0·080 to 3·45 MeV. These small-diameter sources were mounted at the beam spot position and measurements were made at each angle used in the distribution measurements. Further measurements were made, after the irradiations, on the activity from the decay of ^{44}Sc produced in the target. The results of these measurements were used to correct the raw data as a function of observation angle.

5.3. Angular distribution analysis

The measured γ ray distributions were least-squares fitted with an even-order Legendre polynomial expansion of the calculated angular distribution for a range of spin sequences, as a function of the multipole mixing ratios. The formalism of Rose and Brink (1967) was used with substate population parameters calculated using a program based on the compound nucleus statistical model (Hauser and Feshbach 1952) as described by Sheldon and Van Patter (1966). Before proceeding to the results the validity of this approach under the conditions of the present experiment will be briefly discussed.

The technique of aligning the residual nucleus by populating the state of interest near threshold following a compound nucleus reaction, thereby restricting the orbital angular momentum of the outgoing particle and therefore the substate population of the residual state, is well established (Sheldon and Van Patter 1966, Birstein *et al* 1968, Pilt *et al* 1970, Twin *et al* 1970, McEllistrem *et al* 1970, Robertson *et al* 1971). Model dependence is introduced into the calculation of the population parameters with the assumptions that one is averaging over many levels in the compound nucleus, and that the transmission coefficients for the various orbital angular momenta which may contribute in the exit and entrance channels are correctly given by the optical model.

The assumption that the (p, n) reaction proceeds via a compound nucleus mechanism is reasonable for this mass region (see for example McMurray *et al* 1967, de Waal *et al* 1971) and for the proton energy range 4·9 to 6·5 MeV which corresponds to an excitation of 11·7 to 13·2 MeV in the compound nucleus ^{45}Sc. The level spacing at this excitation energy, which can be calculated, or estimated semi-empirically using data on the levels of ^{45}Sc (Endt and van der Leun 1967) and an Ericson plot (Ericson 1959), is less than 0·1 keV. Although the dependence of the results on the transmission coefficients is reduced when measurements are made very close to threshold, this situation does not correspond to the optimum conditions for averaging over many levels. Consequently, a compromise must be made. In the present study γ ray distributions were measured at several proton energies; for example, at 4·9 and 5·15 MeV for the 235 keV state corresponding to 136 and 380 keV above threshold; at 5·15 and 5·30 MeV for the 425 keV state corresponding to 190 and 336 keV above threshold; at 5·15, 5·30 and 5·75 MeV for the 531 keV state corresponding to 86, 230 and 670 keV above threshold, etc. In these cases a large number of levels may be excited in the compound nucleus.

The γ ray distributions which were fitted at each of these energies, retained their characteristic shape. Since one is averaging over a range of emitted neutron energies, the population parameters were calculated at the average neutron energy appropriate for s-wave neutrons, that is at three-fifths of the maximum neutron energy. The substate populations were also calculated at the extremes of the possible neutron energies and the data were fitted with each of these sets of parameters. Detailed thick target excitation functions were measured for several of the states and the yield was found to be proportional to $(\Delta E)^{3/2}$ where ΔE is the emitted neutron energy, as is expected for predominantly s-wave emission.

Average optical model parameters (Wilmore and Hodgson 1964, Rosen *et al* 1965) were used to calculate the penetrabilities. Varying these parameters between reasonable limits produced insignificant changes in the substate population parameters. Similarly, the population parameters are only slightly different for positive and negative parity.

The final point to be made is that the fits to the γ rays from a particular state were made with the same set of population parameters.

The ground state spin of ^{44}Sc is known to be 2 (Harris and McCullen 1961).

5.4. Results

5.4.1. The 235 keV state. The 235 keV state decays by two strong transitions to the ground state ($J = 2$) and to the first excited state at 68 keV. The weak branch to the 146 keV state was not suitable for distribution measurements. The 68 keV state is known to have a spin of 1 (Glass and Kliwer 1968) although the parity was unassigned. The spin and parity of this state were independently determined as 1^- (see § 5.4.3).

The angular distributions and χ^2 fits at a proton energy of 4·90 MeV are shown in figure 6. Similar data at 5·15 MeV were reported earlier (Dracoulis *et al* 1973b). The fits to the ground state transition limit the spin (at the 0·1 % confidence level) to 2 or 3 and of these only the spin 2 gives an acceptable fit to the distribution from the transition to the first excited state. The transition strengths have been previously discussed (Dracoulis *et al* 1973b).

The 235 keV state has only been observed in the ^{46}Ti(d, α)^{44}Sc (Wallen and Hintz 1972) and the ^{44}Ca(^{3}He, t)^{44}Sc reactions (Manthuruthil and Prosser 1972) in which *l*

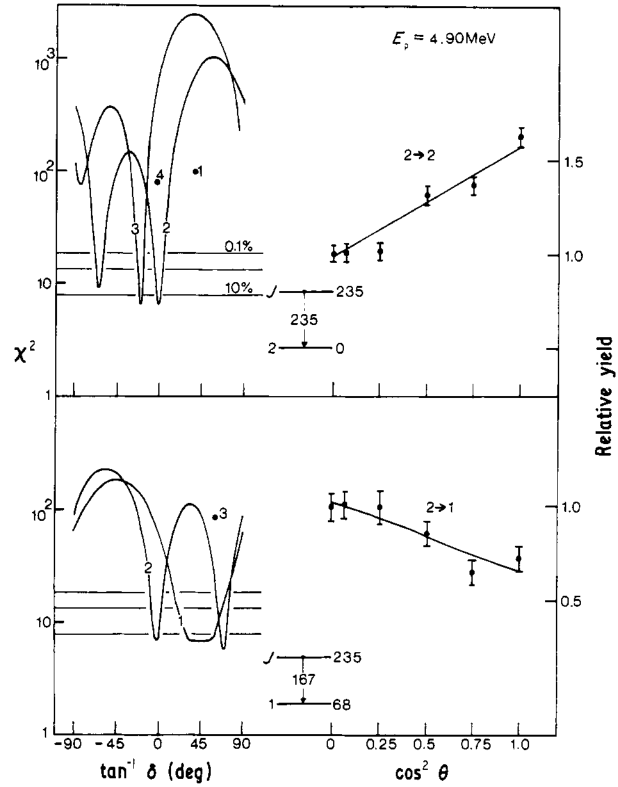

Figure 6. On the right, the measured angular distributions of the γ rays from the 235 keV state plotted as a function of $\cos^2 \theta$. The γ rays were observed following the ^{44}Ca(p, nγ)^{44}Sc reaction at a bombarding energy of 4·90 MeV. On the left the results of the χ^2 fits for various possible spins for the 235 keV state plotted as a function of the arctangent of the mixing ratio δ of the transition. The χ^2 fits are labelled with the appropriate spin of the 235 keV state. The full points are the minima in the χ^2 diagram over the full range of δ for the indicated spin values. The measurement and analysis of the γ ray angular distribution is discussed in § 5 of the text.

values gave negative parity, and a spin of 2 or 3 was favoured. Taken together these results fix the spin and parity of the 235 keV state as 2^-.

5.4.2. The 350 keV state. The 350 keV state decays by a single transition to the ground state. The angular distributions and fits are illustrated in figure 7. These were measured at proton energies of 5·15 and 5·30 MeV. In both cases only a spin of 4 with a pure quadrupole transition gives an acceptable fit to the data. The measured lifetime of (4·52 ± 0·43) ns gives an E2 strength of 3·7 Wu (Weiskopf units), or an M2 strength of 150 Wu. The latter alternative can be rejected and the spin and parity of the 350 keV state are fixed as 4^+.

This confirms the results of the particle reactions which strongly favoured a spin and parity of 4^+ for this state.

5.4.3. The 425 keV state. The 425 keV state decays by a strong transition to the 68 keV state and by weaker branches to the ground, and the 235 keV state. The angular distributions for all these transitions were measured at 5·15 MeV and 5·3 MeV. The data at

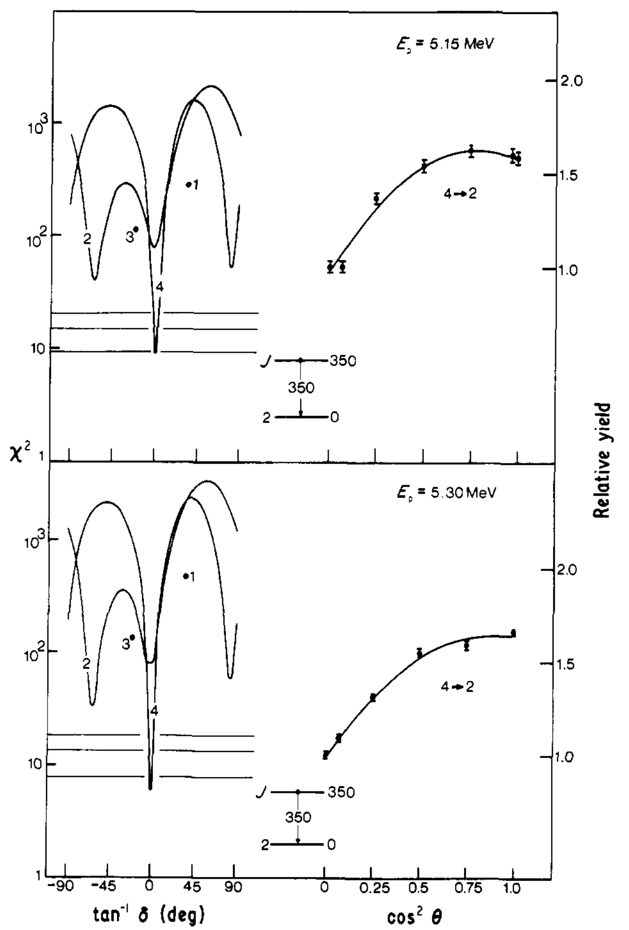

Figure 7. The angular distributions and χ^2 fits for the 350 keV γ ray to the ground state following the $^{44}Ca(p, n\gamma)^{44}Sc$ reaction at bombarding energies of 5·15 and 5·30 MeV (see figure 6).

5·15 MeV have previously been reported (Dracoulis *et al* 1973b) so only the 5·3 MeV results are illustrated in figure 8.

The parity of the 425 keV state was assigned as positive by Schwartz (1968) following the observation of a mixed $l = 1+3$ transition in the $^{43}Ca(^3He, d)^{44}Sc$ reaction. Later work by Ohnuma and Sourkes (1971), Manthuruthil and Prosser (1972) and Wallen and Hintz (1972), however, assign negative parity to this state. As pointed out by several of these authors the contradiction may be due to a mis-assignment in the earlier work because of the weak cross section to this state. It is assumed therefore that the parity of this state is negative.

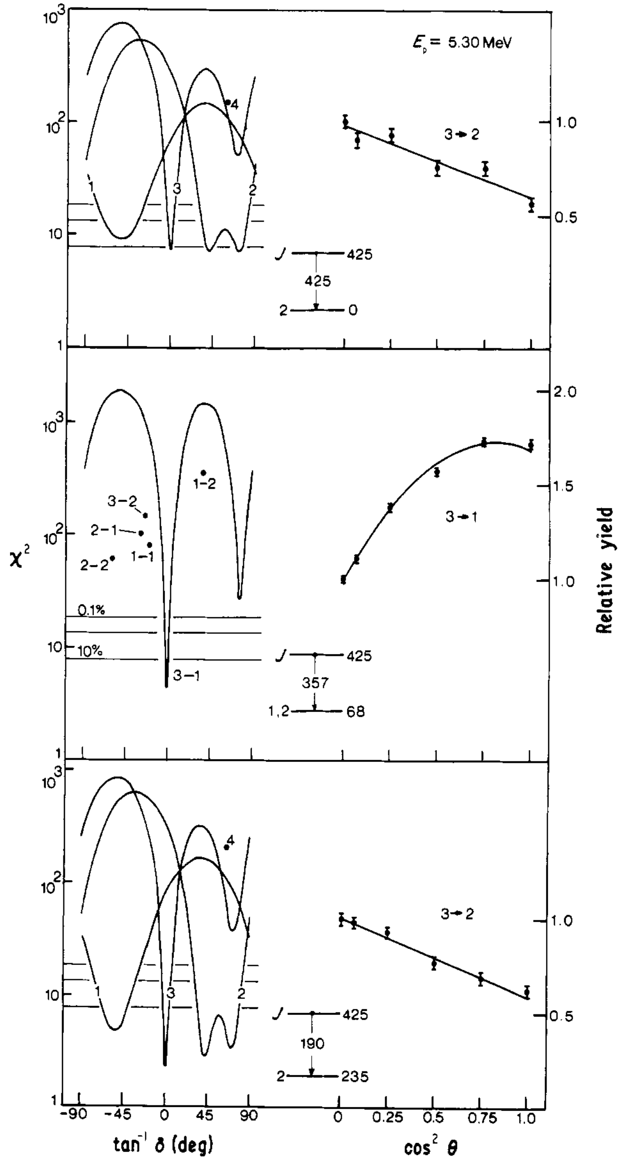

Figure 8. The angular distributions and χ^2 fits for the three transitions from the 425 keV state at a proton energy of 5·30 MeV in the $^{44}Ca(p, n)^{44}Si$ reaction (see figure 6).

As can be seen from figure 8 the distribution data to ground and to the 68 keV state are only consistent with a spin of 3 for the 425 keV state and with a spin of 1 for the 68 keV state. Further, the measured lifetime of 546 ± 60 ps establishes the E2 nature of the 357 keV quadrupole transition to the 68 keV state. Therefore the spins and parities of the 425 and 68 keV states are fixed as 3^- and 1^- respectively.

Although the fit to the angular distribution of the 190 keV branch to the 235 keV state was not required to fix the spin of the 425 keV state the results are consistent with a pure transition from a spin 3 state. Alternatively, having fixed the 425 keV state spin as 3, this distribution could be used as an independent means of limiting the spin of the 235 keV state. In that case, starting with a spin of 3 for the 425 keV state the results would be inconsistent with a spin of 1 for the 235 keV state. For a spin of 3, the data would be fitted with a minimum χ^2 of 11 (which is outside the 10% level but inside the 0·1% level) with a mixed quadrupole–dipole transition with $\delta = 1{\cdot}0$. From the lifetime of the 425 keV state this would require an E2 admixture of about 85 Wu. This E2 strength could not be rigorously excluded but the results would strongly favour a spin of 2 for the 235 keV state. Of course, this spin was determined from the data for transitions from the 235 keV state. It is pointed out to show that several independent arguments exist to limit the spins because of the large number of transitions between the low-lying states.

5.4.4. The 531 keV state. Angular distributions from the 531 keV state were measured at 5·15, 5·30 and 5·75 MeV. This state decays to ground and to the 235 keV state, and by weaker branches to the 68 and 351 keV states. The last transition was too weak for distribution measurements. The results at 5·15 MeV are not shown but are essentially identical to those obtained at the higher energies. Also the data for the 463 keV 531 → 68 keV transition are not shown because of poor statistics but they were consistent with the results for this branch obtained at the higher energy.

The results of the fits at 5·30 and 5·75 MeV are shown in figures 9 and 10. The ground state transition limits the spin to 2 or 3. Similar fits to the transition feeding the 235 keV state favour a spin of 2 or 3. The parity of this state is not known from particle reactions as it is only observed in the ^{46}Ti(d, α)^{44}Sc reaction. Further, the lifetime is only limited to the range $5\,\text{ps} < \tau < 50\,\text{ns}$. Taking the upper limit on the lifetime a spin of 2^+ requires a mixed M2/E1 transition to the 235 keV state, with an M2 admixture of more than 7·6 Wu. The 2^- possibility requires an M2 admixture in the ground state transition of more than 0·33 Wu. Further, the 2^- alternative would give an M2 transition to the 351 keV (4^+) state of greater than 3·5 Wu.

Although none of these multipolarities can be rigorously discarded, taking the fact that these are lower limits on the M2 strength together with the poor fit to the angular distribution of the 531 → 68 keV transition for a spin of 2, a spin of 3 must be favoured. Similarly the limit on the M2 strength of the 531 → 68 keV transition of greater than 0·3 Wu favours negative parity for the 531 keV state but positive parity cannot be excluded.

5.4.5. The 631 keV state. The 631 keV state decays to the 235 keV (2^-) state, to the 350 keV (4^+) state and to the 425 keV (3^-) state. Angular distributions of the first two of these transitions were measured at proton energies of 5·75 and 6·0 MeV. The data at 5·75 MeV were presented previously, and the results at 6·0 MeV are shown in figure 11. Since these results are very similar to those discussed earlier (Dracoulis *et al* 1973b), the arguments will not be presented in detail. The $J^\pi = 4^-$ assignment with pure dipole and

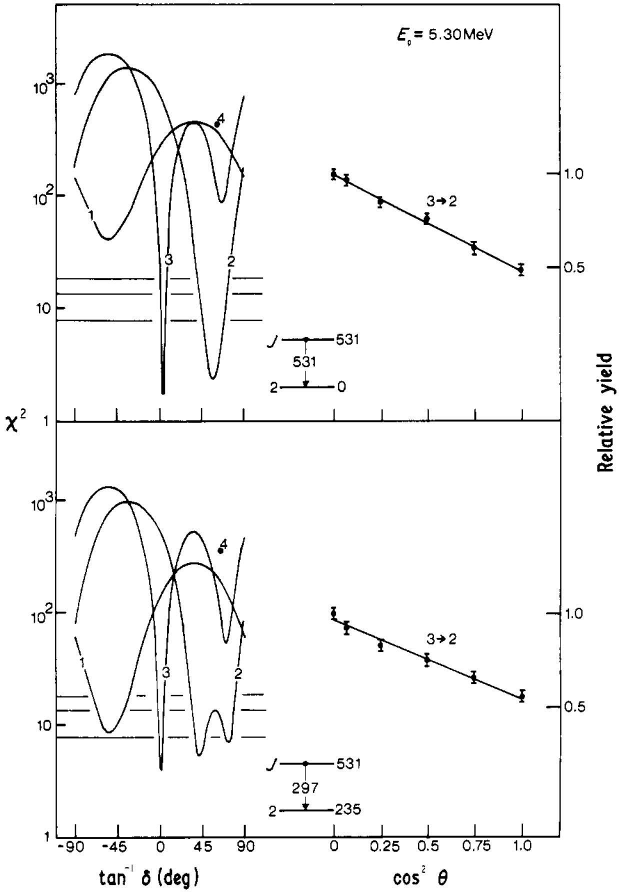

Figure 9. The angular distributions and χ^2 fits for the two transitions from the 531 keV state at a proton energy of 5·30 MeV (see figure 6).

quadrupole transitions is the only acceptable solution, since the other spin alternatives require very strong M2 and E3 admixtures.

This state is known to have negative parity from the particle reaction data. It was observed in the (d, α) reaction (Bjerregaard *et al* 1964), $l = 2$ transfer was assigned in the (d, t) reaction (Ohnuma and Sourkes 1971) and $l = 0$ was assigned in the (^{3}He, d) reaction (Schwartz 1968). These results favoured a 3^- or 4^- spin whereas an $l = 5$ assignment in the (^{3}He, t) reaction (Manthuruthil and Prosser 1972) favoured 4^- or 5^-.

The 4^- assignment of the present work is again in agreement with the only consistent assignment of the particle reaction data.

5.4.6. The 667 keV state. The angular distribution of the 667 keV ground state transition was measured at 5·30 and 5·75 MeV proton energies. Only a weak anisotropy was observed. The fits to the measured distribution were inconsistent with a spin of 4 for this state, but were acceptable for $J = 2$ with $\delta = 0{\cdot}36 \pm 0{\cdot}06$ and for $J = 3$ with

$$\delta = -0{\cdot}14 \pm 0{\cdot}03.$$

The χ^2 fit for a spin of 1 was shallow with a minimum at $\delta = 0{\cdot}09 \pm 0{\cdot}11$ which overlaps

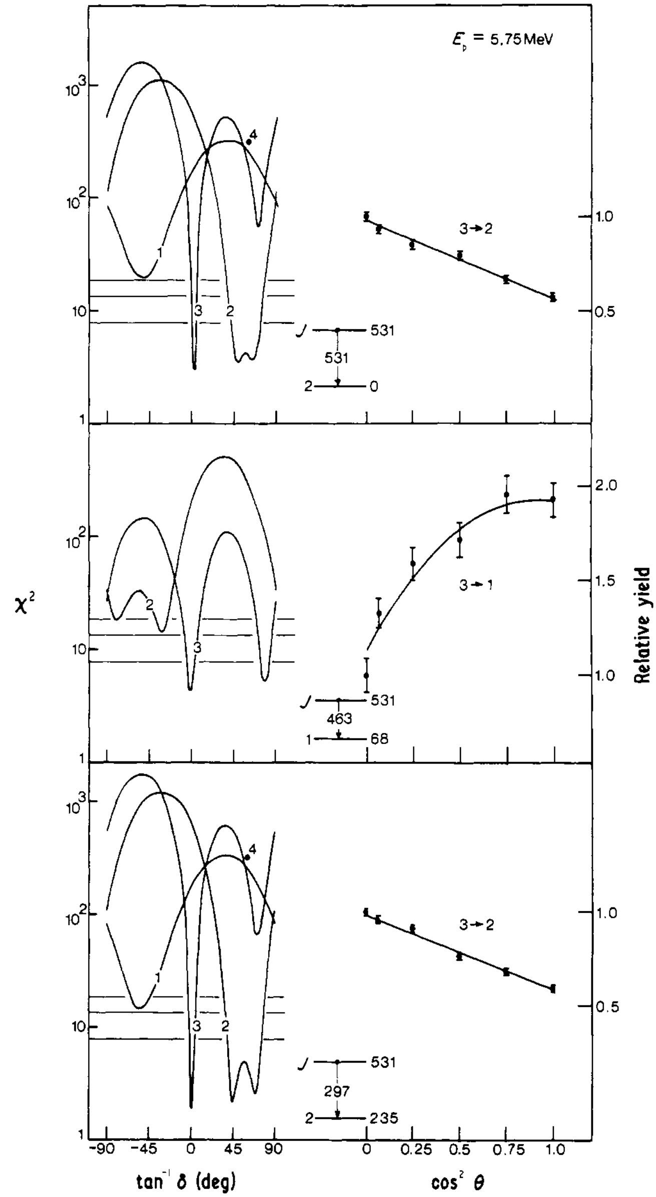

Figure 10. The angular distributions and χ^2 fits for the three transitions from the 531 keV state at a proton energy of 5·75 MeV (see figure 6).

a zero mixing ratio. The lifetime of the state was measured as $0{\cdot}07^{+0{\cdot}014}_{-0{\cdot}02}$ ps which gives E2 admixtures of 1100 ± 300 Wu and 182 ± 45 Wu for the spin 2 and spin 3 alternatives respectively. For the spin 1 case the admixture would be less than 350 Wu. This eliminates spin 2 and makes spin 3 doubtful.

The particle reaction studies of Schlegel *et al* (1970), Ohnuma and Sourkes (1971), Wallen and Hintz (1972) and Manthuruthil and Prosser (1972) strongly favour a 1^+ assignment for the 667 keV state.

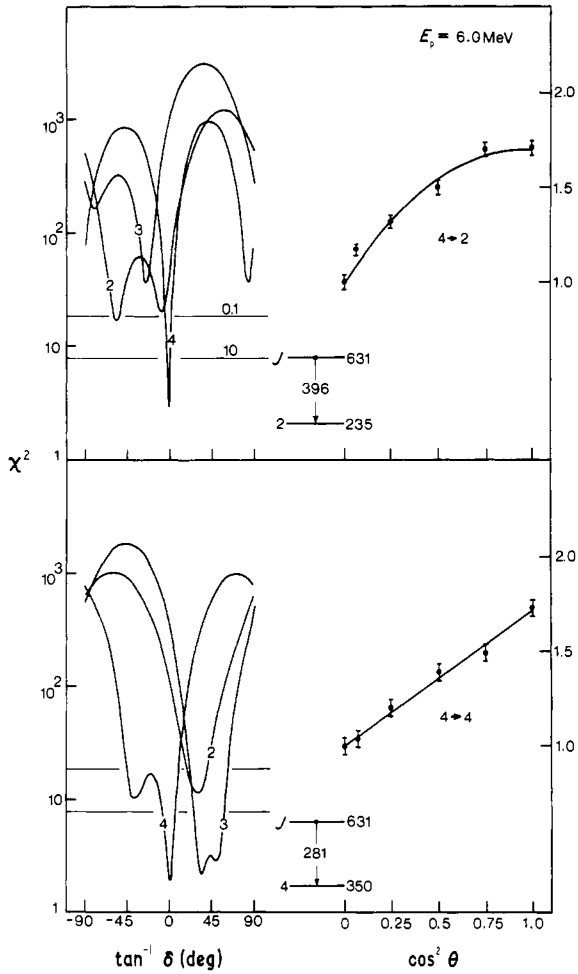

Figure 11. The angular distributions and χ^2 fits to two of the transitions from the 631 keV state at a proton energy of 6·0 MeV (see figure 6).

Therefore the 667 keV state is assigned spin 1 with a less probable spin 3 alternative. The M1 transition strength to ground is 1·52 Wu.

5.4.7. The 763 keV state. The 763 keV state decays mainly to ground, and by a weak (7 %) branch to the 350 keV (4^+) state. The distributions for the ground state transitions, measured at proton energies of 5·75 and 6·0 MeV, are illustrated in figure 12. The fits to the data are consistent with a spin of 3 for this state, with an essentially pure dipole transition to ground or with a spin of 2 with a strongly mixed ($\delta \geqslant 1{\cdot}0$) quadrupole–dipole transition. From the lifetime of the state (0·31 ± 0·02 ps), the spin 2 solution would require an E2 admixture, assuming the parity of the state is positive, of 500 Wu. Further, the 7 % branch to the 4^+ state would correspond to a 1650 Wu E2 or $6{\cdot}7 \times 10^4$ Wu M2 transition. Therefore the spin of the 763 keV state is assigned as 3.

This state has been observed in most of the particle reactions and has been assigned positive parity from the (p, d) (Kashy 1964), (^{3}He, d) (Schwartz 1968), (d, t) (Ohnuma and

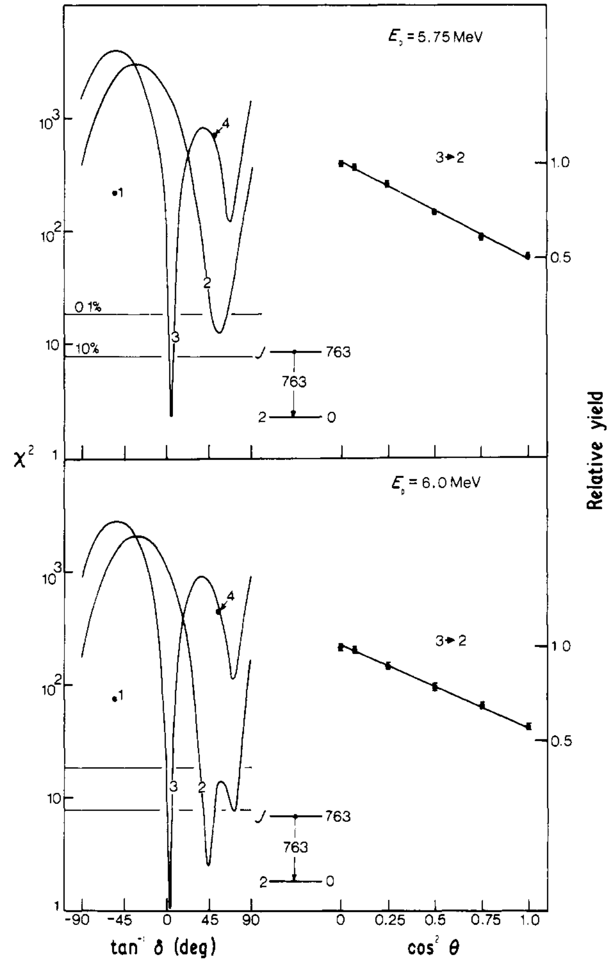

Figure 12. The angular distributions and χ^2 fits as a function of the mixing ratio δ for the ground state transition from the 763 keV state at proton energies of 5·75 and 6·0 MeV (see figure 6).

Sourkes 1971), (^{3}He, α) (Rapaport *et al* 1971), (d, α) (Wallen and Hintz 1972) and the (^{3}He, t) reactions (Manthuruthil and Prosser 1972). These studies favour a spin of 3^+ for this state in agreement with the present assignment.

The strengths of the M1 transitions to ground and to the 350 keV (4^+) state are (0·21 ± 0·02) and (0·10 ± 0·03) Wu respectively.

5.4.8. The 1186 keV state. This state decays by transitions to ground and to the 350 keV (4^+) state. The fit to the ground state transition distribution, measured at 6·0 MeV, is shown in figure 13. Unfortunately, the 836 keV γ ray from the transition to the 4^+ state was not clearly defined in the spectra and therefore a reliable distribution was not measured.

The data are fitted with a pure dipole transition for a spin 3, and with a strongly mixed transition for a spin of 2. A spin of 1 can be rejected because of the strong branch to the 4^+ state. The lifetime of the 1186 keV state was measured to be 0·06 ± 0·02 ps. The

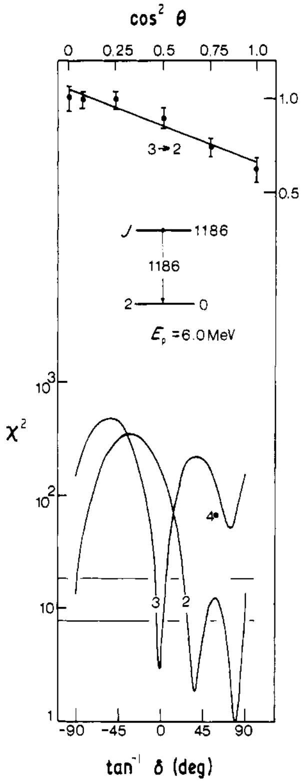

Figure 13. The γ ray angular distributions and χ^2 fits for the ground state transition from the 1186 keV state. The distribution was measured at a proton energy of 6·0 MeV (see figure 6).

quadrupole admixture in the 1186 keV transition for a spin 2 would be about 250 Wu of E2 strength. Further, the spin 2 would require an E2 strength of 2200 Wu for the 836 keV branch to the 4^+ state. Consequently the 1186 keV state is assigned a spin of 3.

From the *l* values assigned in the neutron pick-up reactions, the spin and parity of this state was restricted to the range 2^+–5^+ (Ohnuma and Sourkes 1971, Rapaport *et al* 1971). This range was in agreement with the work of Schwartz (1968) while the results of Manthuruthil and Prosser (1972) and Wallen and Hintz (1972) favoured spin and parity 3^+.

5.4.9. The 1326 keV state. The γ ray angular distributions for the ground state transition of the 1326 keV state are shown in figure 14. These data were measured at proton energies of 6·3 and 6·5 MeV. The distribution of the 56 % branch to the 350 keV (4^+) state was not reliably measured because of the proximity of other γ rays. The fits to the data restrict the spin to 3 or 2. The latter alternative requires a large quadrupole admixture with $\delta = 0{\cdot}62$. From the measured lifetime this admixture would be 14·8 Wu of E2 strength. Although this cannot be discounted the spin 2 assignment would make the transition to the 350 keV state an E2 transition of 311 Wu. This is most unlikely, therefore a spin of 3 is assigned to the 1326 keV state.

The 1326 keV level was not observed in the proton stripping or neutron pick-up reactions but it was observed in the $^{46}Ti(d, \alpha)^{44}Sc$ reaction (Bjerregaard *et al* 1964,

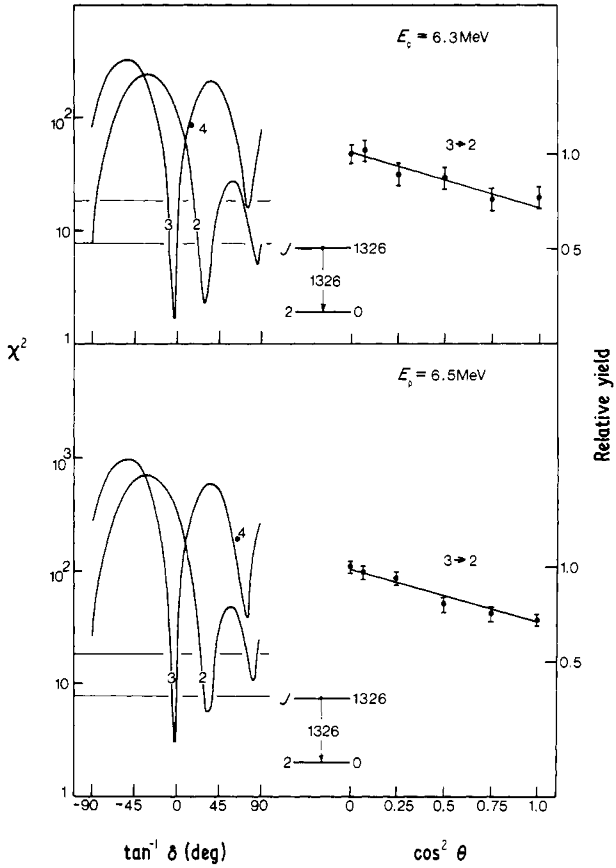

Figure 14. The γ ray distributions and χ^2 fits for the ground state transition from the 1326 keV state measured at proton energies of 6·3 and 6·5 MeV (see figure 6).

Wallen and Hintz 1972) although l values were not assigned. An $l = 4$ transfer was assigned in the (^{3}He, t) reaction (Manthuruthil and Prosser 1972) but the distributions in this reaction are rather structureless. A spin of 3^+ was argued for in that study but mainly on the basis of the (p, γ) measurements (Poirier and Manthuruthil 1971) in which a 658 keV γ ray was assigned as the 1326 → 667 keV transition to the 1^+ state. The coincidence data from the present study place this γ ray elsewhere in the decay scheme.

Therefore the spin of the 1326 keV state is 3 and the parity is probably positive.

5.4.10. The 1426 keV state. The 1426 keV state decays to ground (2^+), to the first excited state (1^-) the 235 keV state (2^-), and the 425 keV state (3^-). The distributions for the first two of these transitions were measured at proton energies of 6·3 and 6·5 MeV. The fits to the ground state transition were consistent with a spin of 1, 2 or 3 while the transition to the 68 keV state was only fitted with a spin of 1 or 2. Therefore the spin of this state is restricted to 1 or 2. The lifetime of the 1426 keV state was not measured, therefore arguments based on the transition strengths cannot be made.

The evidence from the particle transfer reactions for a state at 1426 keV is conflicting since both positive and negative parity have been assigned. For example, Kashy (1964) assigned negative parity to a state at about 1410 keV while Schwartz (1968) assigned positive parity to a state at about 1433 keV. Ohnuma and Sourkes (1971) have assigned negative parity to a state at 1415 keV and Rapaport *et al* (1971) assign the same parity to a state at 1424 keV. Finally, Manthuruthil and Prosser (1972) argue for a spin 3^+ or 4^+ state at 1427 keV. This last result is in disagreement with the present work which assigns spin 1 or 2. The parity is not established and it is possible that there is more than one state at about this energy. Negative parity may be favoured for this level because of the transitions to the low-lying negative parity states.

5.4.11. Other states. Many of the states in ^{44}Sc were only weakly excited in the ^{44}Ca (p, n) reaction and therefore were not suitable for γ ray distribution measurements near threshold. Nevertheless the γ decay of these states was consistent with the spin limits obtained in the direct reaction studies.

In particular, the 1006 keV state was populated in the (d, t) reaction with an $l = 0+2$ transfer (Ohnuma and Sourkes 1971). The spin and parity is limited to $(2–5)^-$. The observed γ decay to the 2^-, 4^+, 3^- and 4^- states would favour a spin of 3 or 4 for this state.

The 987 keV state was observed to decay only to ground. This is consistent with the results of Schlegel *et al* (1970) which suggest a spin and parity of 3^+ or 4^+ for a state at about this energy. The measured lifetime of $2{\cdot}0^{-0{\cdot}5}_{+0{\cdot}9}$ ps corresponds to an M1 strength of 0·017 Wu or an E2 strength of 47 Wu.

Table 3. Spin and parity assignments and mixing ratios measured in this work. The final column of accepted values includes parities from the particle reactions as discussed in the text. The parentheses indicate likely assignments where the results are ambiguous

Level energy (keV)	Assignment J	π	Transition	Mixing ratio δ	Adopted J^π
68	1				1^-
146					0^-
235	2		235 → 68	−0·02 ± 0·02 or 2·5 ± 0·2	2^-
			235 → 0	0·0 ± 0·05	
350	4	+	350 → 0	0·01 ± 0·04	4^+
425	3		425 → 235	−0·02 ± 0·06	3^-
			425 → 68	0·0 ± 0·03	
			425 → 0	−0·03 ± 0·06	
531	(3)		531 → 235	0·02 ± 0·03	(3^-)
			531 → 68	−0·02 ± 0·07	
			531 → 0	0·04 ± 0·03	
631	4		631 → 350	0·02 ± 0·09	4^-
			631 → 235	−0·02 ± 0·03	
667	(1)		667 → 0	0·09 ± 0·11	1^+
763	3		763 → 0	0·06 ± 0·04	3^+
1186	3		1186 → 0	−0·02 ± 0·04	3^+
1326	3		1326 → 0	−0·06 ± 0·04	3^+
1426	(1)		1426 → 68	1·0 ± 1·1	
			1426 → 0	$0{\cdot}86^{+1{\cdot}3}_{-0{\cdot}6}$	$(1, 2)^{(-)}$
	(2)		1426 → 68	0·0 ± 0·09	
			1426 → 0	0·23 ± 0·07	

As summarized by Manthuruthil and Prosser (1972) the 1052 keV state has a probable spin and parity of 5^+. This is in agreement with the present results which show that this state decays only to the 350 keV (4^+) state. The lifetime has been measured to be $0.24^{-0.06}_{+0.08}$ ps. This would correspond to an M1 strength of $0.38^{+0.09}_{-0.12}$ Wu.

Table 4. The theoretical (Pauli 1967) and experimental (Ristinen and Sunyar 1967) conversion coefficients for the 68 and 78 keV transitions in ^{44}Sc

E_γ (keV)	Experiment	Theory			
		E1	M1	E2	M2
68	0·123 ± 0·023	0·095	0·051	1·58	0·73
78	0·031 ± 0·005	0·059	0·035	0·91	0·43

Finally, the 1196 keV state has a possible assignment of 5^- from the (d, α) work of Wallen and Hintz (1972). This spin and parity is consistent with the present work in which transitions to the 6^+ state, to the 3^- state and to the 4^- state were observed.

The results of the spin assignments and the measured mixing ratios are summarized in table 3.

6. The 68 and 146 keV states

In the light of the present results it is useful to re-evaluate the existing data on the 68 and 146 keV states which have been extensively studied since they are populated in the β decay of ^{44}Ti. The interpretation of the earlier data on these two states (Bergstrom and Thieberger 1962, Kliwer *et al* 1963, Glass and Kliwer 1968, Ristinen and Sunyar 1967) was hampered because it was believed incorrectly that the ^{44}Ti – ^{44}Sc ground state energy difference was only 155 keV. Later work (Simpson *et al* 1969) showed that the mass difference was 272 keV and that therefore the 146 keV state was fed by electron capture with a lg*ft* of 6·5 while the 68 keV state has a lg*ft* of $8.6^{+1.9}_{-0.2}$. Only allowed transitions from the 0^+, ^{44}Ti ground state were considered previously.

In the present work measurements on the transitions from the 425 keV state (see § 5.4.3) fix the spin and parity of the 68 keV state as 1^-. This is not inconsistent with the lg*ft* to this state.

Recent calculations of the internal conversion coefficients for Sc (Pauli 1967, private communication by J S Geiger) can now be used, together with the previous data, to limit the spin and parity of the 146 keV state. The theoretical and experimental conversion coefficients are listed in table 4. From the table it is apparent that the 78 keV transition (146 → 68 keV) is only consistent with a pure M1 multipolarity. Taking limits of one standard deviation, the maximum E2 admixture is 0·1 %. Therefore, the parity of the 146 keV state is the same as that of the 68 keV state, negative.

The conversion coefficient for the 68 keV transition is consistent (at the extreme of one standard deviation) with a pure E1 transition. The maximum M2 admixture is 8 %. Taking these limits on the quadrupole admixtures, the weighted mean of the measured 68–78 keV γ–γ correlation (Ristinen and Sunyar 1967, Glass and Kliwer 1968) of $A_2 = 0.045 \pm 0.003$ is consistent with a spin sequence for the 146 → 68 → 0 keV states of $2^- \rightarrow 1^- \rightarrow 2^+$, $1^- \rightarrow 1^- \rightarrow 2^+$ and $0^- \rightarrow 1^- \rightarrow 2^+$. The first two of these possibilities

Table 5. Transition strengths between the low-lying positive parity states in ^{44}Sc

Level energy (keV)	J^{π}	τ	Decay to keV, J, %	Transition strengths (Wu) M1	E2
350	4^+	4.5 ± 0.4 ns	0, 2^+, 100		3.7 ± 0.4
667	1^+	$0.07^{-0.02}_{+0.014}$ ps	0, 2^+, 100	$1.52^{+0.4}_{-0.3}$	
763	3^+	0.31 ± 0.02 ps	0, 2^+, 93 ± 2 350, 4^+, 7 ± 2	0.21 ± 0.02 0.10 ± 0.03	
987	(3^+)	$2.0^{-0.5}_{+0.9}$ ps	0, 2^+, 100	$0.017^{+0.004}_{-0.007}$	
1052	(5^+)	$0.24^{-0.06}_{+0.08}$ ps	350, 4^+, 100	$0.38^{+0.09}_{-0.12}$	
1186	3^+	0.056 ± 0.016 ps	0, 2^+, 40 ± 6 350, 4^+, 60 ± 6	0.13 ± 0.04 0.55 ± 0.19	
1326	3^+	0.18 ± 0.02 ps	0, 2^+, 44 ± 5 350, 4^+, 56 ± 5	0.033 ± 0.005 0.11 ± 0.02	

require quadrupole admixtures in the 68 keV transition, whereas the $0 \rightarrow 1 \rightarrow 2$ sequence is fitted with pure transitions.

However, a further constraint on the quadrupole admixture in the 68 keV transition is possible since, from the lifetime of the 68 keV state (221 ns), the M2 strength is given by about $110 \times Q$ where Q is the percentage quadrupole admixture. For $Q < 2$ the spin 1 and 2 alternatives for the 146 keV state would be eliminated. Since this limit would correspond to less than 220 Wu of M2 admixture, the only reasonable solution is a spin and parity of 0^- for the 146 keV state.

The measured lg*ft* to the 146 keV state is consistent with a $0^+ \rightarrow 0^-$ first forbidden transition.

7. Discussion

7.1. Negative parity states

^{44}Sc has one proton and three neutrons outside the closed core of ^{40}Ca. In the simplest shell model description the lowest energy states will be those of the $(1f_{7/2})^4$ configuration. To obtain negative parity states particles must be excited either from the $1f_{7/2}$ orbital to the $1g_{9/2}$ orbitals, or out of the $d_{3/2}$ and $s_{1/2}$ orbitals of the core. Both of these processes would be energetically unfavoured in a spherical shell model description of ^{44}Sc. The fact that low-lying states with negative parity are observed indicates the need to include more complicated configurations in the description of this nucleus.

Plendl *et al* (1965) recognized that low-lying deformed states based on the $d_{3/2}$ proton hole configuration could be expected in the odd Sc isotopes. This situation arises because of the increasing proximity of the [202] $K^{\pi} = \frac{3}{2}^+$ and [330] $K^{\pi} = \frac{1}{2}^-$ Nilsson orbitals with increasing deformation. With deformation it is then possible to excite a proton from the $K^{\pi} = \frac{3}{2}^+$ orbital, leaving an odd proton in the same orbital, to the $K^{\pi} = \frac{1}{2}^-$ orbital with a minimum of energy loss. Such a proton excitation is also favoured because of the extra binding energy gained in forming a ^{4}He type cluster outside the core (Plendl *et al* 1965, Spicer and Danos 1971). Rotational bands based on these deformed configurations are now well established in the neighbouring odd Sc isotopes as has been recently reviewed by Maurenzig (1971). Evidence for similar bands in ^{46}Sc has also been presented (Raju and Spicer 1970, Dracoulis *et al* 1973a).

In ^{44}Sc a proton excitation from the $K^\pi = \frac{3}{2}^+$ orbital of the $(d_{3/2})$ state will result in rotational bands with $K^\pi = 0^-$ and 3^- from the antiparallel and parallel coupling of the odd proton in the [202] $K^\pi = \frac{3}{2}^+$ orbital and the odd neutron in the [321] $K^\pi = \frac{3}{2}^-$ orbital. On the basis of the present work it was recently proposed (Dracoulis *et al* 1973b) that the 68, 146, 235, 425, and 631 keV states were the 1^-, 0^-, 2^-, 3^- and 4^- members of a $K^\pi = 0^-$ band. The energies of these states are shown in figure 15, plotted against

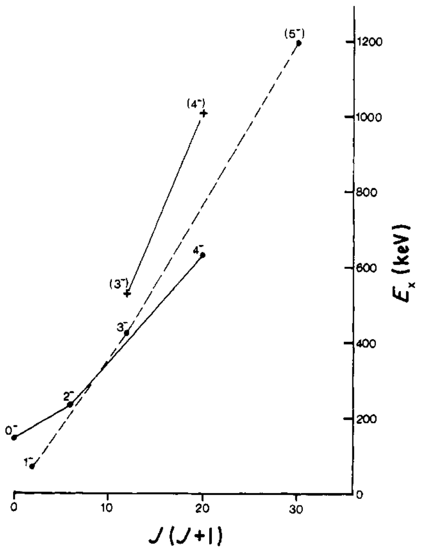

Figure 15. The energies of the low-lying negative parity states plotted as a function of $J(J+1)$. The lines connect the odd and even members of the proposed $K^\pi = 0^-$ band, and the members of the $K^\pi = 3^-$ band (see § 7).

$J(J+1)$. Also included are the 1006 keV state which has a possible spin and parity of 4^-, and the 1197 keV state which has a tentative assignment of 5^-. These may be the next members of bands based on the possible 3^- state at 531 keV, and on the 0^- state. The identification of these bands would, at least qualitatively, explain all the negative parity states below 1·5 MeV in ^{44}Sc. Of course the situation is not as simple as this discussion might indicate because, apart from the deviations from the $J(J+1)$ spacing of the levels, which could be explained by mixing from other bands, the enhanced E2 transition strengths between J and $J-2$ members of the $K^\pi = 0^-$ band are not in the ratio expected from the simple rotational model. The $3^- \to 1^-$ E2 transition is 16 Wu while the $4^- \to 2^-$ is only 6·4 Wu. The rotational model predicts a ratio of 10/9. It is noted that the former transition strength corresponds, for a spheroidal rotor, to a deformation β of about 0·24 in good agreement with the deformation found in neighbouring nuclei. The limit on the branching ratio of the $2^- \to 0^-$ transition ($\leqslant 2\%$) corresponds to an E2 strength of 17·4 Wu or less. Further, as was pointed out previously (Dracoulis *et al* 1973b) the experimentally observed retardation of M1 transitions between J and $J-1$ members of the 0^- band implies cancellation in the M1 transition matrix element which is proportional to $(g_{\Omega_p} - g_{\Omega_n})^2$. These gyromagnetic ratios were calculated as a function of deformation using Nilsson model wavefunctions but the approximate equality of g_{Ω_p} and g_{Ω_n} was not reproduced.

A different approach has been used by Johnstone (1970). To calculate the negative parity states, a $d_{3/2}$ proton hole was coupled to the low-lying negative parity states of ^{45}Ti. The ^{45}Ti wavefunctions were projected from Hartree–Fock intrinsic states. This method describes ^{45}Ti as a deformed nucleus but the final states in ^{44}Sc do not have any simple band structure. The initial calculations gave a set of states with spins 0^-–5^- at too high an energy, but further calculations (Benson and Johnstone 1973, private communication) have succeeded in depressing the states as is illustrated in figure 16. It is apparent that the correct number of negative parity states is predicted at low energy, but the sequence and energy spacing is not reproduced. Further, using the wavefunctions calculated for these states it is not possible to reproduce the retarded M1 strengths observed experimentally.

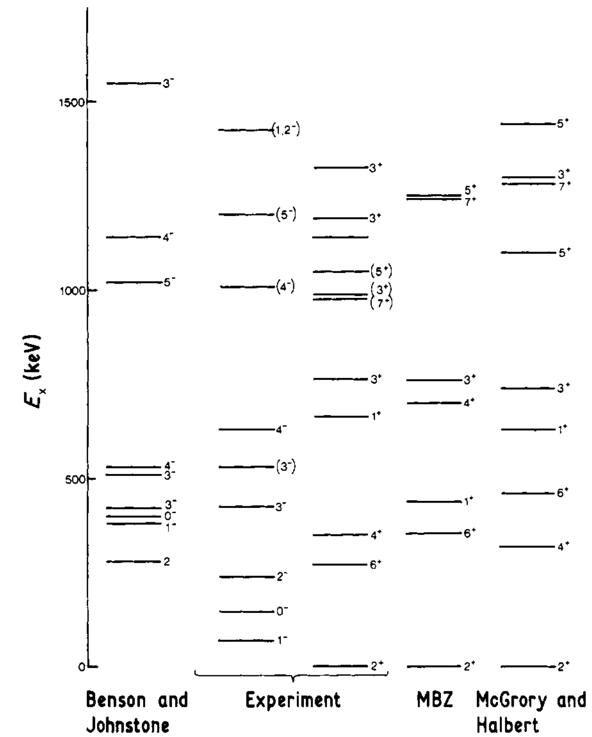

Figure 16. The experimental level scheme is compared with the predicted negative parity states calculated by Benson and Johnstone (1973, private communication) and with the positive parity states predicted by McCullen *et al* (1964, MBZ) and McGrory and Halbert (1971). The details of the calculations are discussed in the text (§ 7).

7.2. The positive parity states

Shell model calculations of the states of ^{44}Sc have been made by McCullen *et al* (1964, to be referred to as MBZ) and Schwartz (1968). These calculations are similar in that they restrict the configurations to $(1f_{7/2})^4$ and that they use an effective interaction determined from the neighbouring nucleus ^{42}Sc. The low energy spectrum from these calculations is compared in figure 16 with the positive parity states known from experiment.

The particle transfer results of Schwartz (1968). Ohnuma and Sourkes (1971) and Schlegel *et al* (1970) suggest that the 2^+ ground state, 6^+ (271 keV), 4^+ (350 keV), 1^+ (667 keV), 3^+ (763 keV), 7^+ (974 keV), 5^+ (1052 keV) and 3^+ (1186 keV) states are possible candidates for the predicted members of the $(1f_{7/2})^4$ configuration. The magnetic moments of the 2^+ and 6^+ states (Harris and McCullen 1963) have been reproduced by Bayman *et al* (1963) using the MBZ wavefunctions and effective proton and neutron magnetic moments chosen for a series of $1f_{7/2}$ shell nuclei.

It is apparent from the comparison in figure 16 that, although there is qualitative agreement below 1 MeV excitation, there are more positive parity states than can be accounted for by the calculation. Only the states observed in the present study have been included in figure 16 but at higher energies many more states are known and the comparison is even less favourable.

More extensive shell model calculations have been carried out in which the configuration space was extended to include some $(fp)^4$ configurations (McGrory and Halbert 1971). Despite the extent of these calculations, agreement with experiment is not improved, at least in the density of levels.

A more sensitive test of the identification of the positive parity states with shell model configurations would be in a comparison of transition strengths. It is noted from table 5 that the M1 strengths of $\Delta J = 1$ transitions between the positive parity states are close to or greater than the Weiskopf single particle estimates. For simple configurations these enhancements are expected since the M1 transitions between $\Delta J = 1$ states have a large contribution in the M1 matrix element from the isovector term. Further the E2 strength between $\Delta J = 2$ states should be enhanced as is the case for the observed $4^+ \rightarrow 2^+$ transition of 3·7 Wu. Detailed estimates of the transition strengths are not available from the various calculations. These would be useful both as a test of the proposed configurations, and of the effective E2 charges and moments in the $1f_{7/2}$ shell.

8. Conclusion

The γ decay modes, spins and lifetimes of the excited states of ^{44}Sc up to 1·5 MeV excitation have been determined. The many negative parity states at low energy are identified as members of deformed bands based on the $(d_{3/2})$ proton hole configuration. The positive parity states arise from spherical $(fp)^4$ configurations. This coexistence between spherical and deformed states gives qualitative agreement between theory and experiment but more detailed calculations of the properties of these states, particularly transition strengths is necessary before the validity of this simple picture is established.

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