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Spin assignments for some higher excited states in ^{34}S

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Abstract. The levels of ^{34}S from 5·4 MeV to 7·3 MeV excitation energy have been studied by particle–γ ray angular correlation experiments using the reaction $^{31}P(\alpha, p)^{34}S$. Spin assignments of 2, 3, 4, 4, 1, 2 and 2 have been made to the levels at 5·680, 6·173, 6·250, 6·415, 6·480, 7·112 and 7·220 MeV respectively. Spin restrictions have been placed on other levels and some previous spin assignments have been confirmed. Branching ratios have been determined for many of the observed decay modes and multipole mixing ratios obtained for several transitions.

1. Introduction

Measurements of the electromagnetic decay properties of levels below 5·4 MeV excitation in ^{34}S have been made in this laboratory by Mulhern *et al* (1971). The present work extends these measurements up to an excitation energy of 7·3 MeV. The compilation of Endt and van der Leun (1967) lists twenty levels for 5·4 MeV $< E_x <$ 7·3 MeV with J^π values assigned to six of these levels by means of the $^{32}S(t, p)^{34}S$ reaction (Hinds 1965 private communication). A study of the $^{34}S(p, p')^{34}S$ reaction by Moss (1968) confirmed nineteen of the twenty levels listed by Endt and van der Leun (1967) and revealed the possibility of a further level at 7·26 MeV, but a level listed at 6·53 MeV in previous work was not observed. Levels at 6·22, 6·91 and 7·19 MeV were assigned $J^\pi \leqslant 4^+$ from the $^{35}Cl(d, \tau)^{34}S$ reaction (Puttaswamy and Yntema 1969) and the level at 5·689 MeV, $J^\pi = 5^-$ (Greene *et al* 1971). Levels at 5·680, 6·482 and 6·63 MeV were assigned negative parity (Van der Baan and Sikora 1971) from a study of the $^{33}S(d, p)^{34}S$ reaction.

2. Experimental procedure

Levels of ^{34}S were populated via the $^{31}P(\alpha, p)^{34}S$ reaction by bombarding targets of 100 $\mu g\,cm^{-2}$ red phosphorous on 20 $\mu g\,cm^{-2}$ carbon foils with 9·3 MeV and 11·0 MeV α particles from the Liverpool University tandem accelerator. Angular correlations were obtained by measuring the yield of γ rays de-exciting the levels of ^{34}S and detected in five NaI(Tl) spectrometers positioned around the target, in coincidence with protons stopped in an annular surface barrier detector positioned at 180° to the beam direction. The data obtained at 9·3 MeV bombarding energy included particle γ ray coincidence measurements made with the aid of a 40 cm^3 Ge(Li) detector positioned close to the target. The high resolution coincidence spectra thus obtained enabled several complex decay modes to be clarified.

A further experiment was performed at $E_\alpha = 9{\cdot}3$ MeV with five Ge(Li) detectors positioned around the target. This experiment yielded correlations following the decay of the strongly excited 5·689 MeV level; the earlier experiments (Mulhern *et al* 1971) had shown that several γ rays decaying from this level could not be resolved in the NaI(Tl) detectors.

The experimental apparatus has been described in previous publications (eg Mulhern *et al* 1971). On line data handling was performed using a DEC PDP-7 computer and further off line analysis was carried out on an IBM 360/65 computer.

The phase consistent convention of Rose and Brink (1967) has been used throughout the correlation analysis. Spin hypotheses which yielded minimum χ^2 values lying above the 0·1 % confidence limit have been rejected as possible spin assignments. The quoted value for a multipole mixing ratio δ is taken at the minimum of the plot of χ^2 against $\tan^{-1}\delta$ for those spin hypotheses not rejected by the 0·1 % confidence limit criterion. The error in a multipole mixing ratio was obtained by determining the range of values allowed at the 31·7 % confidence limit of the appropriate F distribution (Cline and Lesser 1970).

3. Results

The Legendre polynomial coefficients obtained from the various measured correlations are given in table 1.

Level energies, spin assignments, branching ratios and multipole mixing ratios obtained from the present and previous work for 5·4 MeV $< E_x <$ 7·3 MeV are presented in table 2 together with the lifetime measurements of Greene *et al* (1970 and private communication) and transition rates assuming that the parity change in a transition is not known. A particle spectrum from the annular detector taken at an α particle bombarding energy $E_x = 9{\cdot}3$ MeV is shown in figure 1.

3.1. The 5·680 and 5·689 MeV levels

Figure 2 shows γ rays in the Ge(Li) detector in coincidence with protons de-exciting levels around $E_x = 5{\cdot}68$ MeV. The 2·377 and 3·553 MeV γ rays are due to the decay of the 5·680 MeV level to the 3·303 MeV (2^+) and 2·127 MeV (2^+) levels respectively while the 1·001 MeV and 1·065 MeV γ rays arise from the decay of the 5·689 MeV level to the 4·688 MeV (4^+) and 4·623 MeV (3^-) levels respectively.

The correlation of the 3·553 MeV transition from the 5·680 MeV level obtained from the NaI(Tl) spectra was fitted for spin hypotheses $J = 1, 2, 3$ and 4 (figure 3) yielding minimum χ^2 values of 26·1, 1·7, 28·4 and 332 respectively. The hypotheses $J = 1, 3$ and 4 were rejected on the grounds that their minimum χ^2 values were higher than the 0·1 % confidence limit. It is apparent from the plot of χ^2 against $\tan^{-1}\delta$ shown in figure 3 that two solutions are possible for the multipole mixing ratio either $\delta = 0{\cdot}47^{+0{\cdot}11}_{-0{\cdot}07}$ or pure quadrupole. No correlation was obtained for the 2·377 MeV transition to the 3·303 MeV level from the NaI(Tl) spectra since these γ rays could not be resolved by the NaI(Tl) detectors from the 2·496 MeV γ rays arising from the decay of the neighbouring 5·689 MeV level. However, the five Ge(Li) detector experiment performed at $E_\alpha = 9{\cdot}3$ MeV to clarify the correlations of decays from the 5·689 MeV level, also revealed 2·377 MeV γ rays from the decay of the 5·680 MeV level. The multipole mixing ratio for the 2·377 MeV γ ray correlation obtained from the Ge(Li) spectra was $\delta > 0{\cdot}4$

Table 1. Legendre polynomial coefficients corrected for the solid angle of the γ ray detectors

E_x (MeV)	E_γ (MeV)	E_α (MeV)	a_2/a_0	a_4/a_0
5·680	3·553	9·3	−0·14±0·02	−0·15±0·02
	2·377†		−0·13±0·12	−0·50±0·14
5·689	1·001†	9·3	−0·32±0·05	−0·22±0·05
	1·065†		0·29±0·07	−0·36±0·07
	1·320†		−0·19±0·08	−0·23±0·08
5·993	5·993	11·0	0·40±0·02	−0·61±0·03
	1·176		−0·08±0·06	0·05±0·07
	2·127		0·14±0·05	0·07±0·06
6·120	2·817	9·3	0·38±0·05	0·06±0·06
	3·303		−0·02±0·09	0·11±0·11
	3·993		0·05±0·05	−0·07±0·06
6·173	2·870	9·3	−0·67±0·06	0·01±0·07
	3·303		0·32±0·05	−0·08±0·06
	1·485		−0·34±0·03	0·06±0·03
	4·046		−0·94±0·04	0·14±0·04
6·250	1·376	9·3	−0·44±0·06	0·63±0·08
	3·303		0·62±0·13	0·08±0·14
6·347	6·347	9·3	0·20±0·05	0·02±0·06
	3·044 } 3·303 }		−0·05±0·03	−0·03±0·03
6·480	4·353	9·3	0·12±0·05	0·05±0·06
	1·176		−0·16±0·02	0·0±0·03
	2·127		−0·04±0·03	0·04±0·04
6·640	0·960	9·3	−0·46±0·08	0·00±0·10
	1·176		−0·30±0·05	0·19±0·07
	2·127		0·15±0·03	0·09±0·04
	2·496		−0·09±0·10	0·23±0·12
	3·303		0·36±0·10	−0·29±0·13
6·731	4·604	9·3	0·50±0·02	−0·27±0·02
	4·604	11·0	0·44±0·02	−0·23±0·02
6·830	6·830	9·3	0·49±0·09	−0·39±0·12
6·864	4·737	9·3	0·50±0·05	−0·25±0·07
	2·561		0·36±0·05	−0·19±0·06
6·950	4·892	9·3	0·21±0·05	−0·45±0·06
7·112	4·985	9·3	0·64±0·03	−0·04±0·03
	7·112		0·70±0·12	−1·03±0·17
7·220	7·220	9·3	0·46±0·04	−0·73±0·05

† The correlation was obtained from the five Ge(Li) detector experiments.

Table 2. Summary of information on ^{34}S (E_x > 5·4 MeV) based on previous work and the present experiment. Transition strengths are calculated assuming the parity change in a transition is not known

Initial level (MeV)	Previous J^π	Present J^π	Final level (J^π) (MeV)	Mixing ratio (present)	Branching ratio (%)	Lifetime† (fs)	$\|M(E2)\|^2$ Wu	$\|M(M2)\|^2$ Wu
5·680	$()^-$	2	2·127(2^+)	$0·47^{+0·11}_{-0·07}$		380±30	0·04±0·01	1·2±0·3
				or quadrupole			0·68±0·06	21·5±1·5
			3·303(2^+)					
5·689	5^-	(3^-)5^-	4·688(4^+)	0·05±0·09	51±2	(54±6) × 10^3		
			4·623(3^-)	E2	49±2		0·82±0·10	28·1±3·5

Table 2—continued

Initial level (MeV)	Previous J^π	Present J^π	Final level (J^π) (MeV)	Mixing ratio (present)	Branching ratio (%)	Lifetime† (fs)	$\|M(E2)\|^2$ Wu	$\|M(M2)\|^2$ Wu
5·753	1^-		2·127(2^+)					
5·848	0^+		2·127(2^+)	E2				
5·993	2^+	2^+	0·0 (0^+)	E2	55 ± 10	<10	>0·9	>30·0
			2·127(2^+)		25 ± 8			
			4·075(1^+)		20 ± 8			
6·120	2^+	(1, 2)	3·303(2^+)	$0·09\pm0·04$ (for $J=2$)	82 ± 7	<75		
			2·127(2^+)		18 ± 7			
6·173	($\leqslant 4^+$)	3^-	2·127(2^+)	$0·43\pm0·16$	20 ± 5	<13	>0·1	>4·0
				or $1·0\pm0·3$			>0·6	>20·0
			3·303(2^-)	$0·23\pm0·07$	38 ± 5	<13	>0·5	>16·0
				or $1·9\pm0·6$			>12·0	>400
			4·688(4^+)	$-0·04^{+0·03}_{-0·06}$	36 ± 5			
			4·892(2^-)		6 ± 5			
6·250	($\leqslant 4^-$)	4^-	4·874(3^+)	$3·7^{+2·6}_{-0·7}$	57 ± 10	390^{+70}_{-40}	$19·0\pm4·0$	600 ± 100
			4·688(4^+)		43 ± 10			
6·347	1^-	1	0·0 (0^+)	dipole	30 ± 10	<36		
			3·303(2^+)	$-0·1\leqslant\delta\leqslant1·2$	70 ± 10			
6·415		4	4·874(3^+)	$0·0\pm0·06$	62 ± 5	<10		
			4·688(4^+)	$0·0^{+0·14}_{-0·32}$	38 ± 5			
6·480	( )$^-$	1	2·127(2^+)	$0·2\leqslant\delta\leqslant2·0$	41 ± 10			
			3·303(2^+)	quadrupole	59 ± 10			
6·640	( )$^-$	($2\leqslant J\leqslant4$)	5·680(2^-)		22 ± 10			
			4·623(3^-)		78 ± 10			
6·731		2^+, 4^+	2·127(2^+)	$-1·8\pm0·3$ ($J=2$)	55 ± 5	<10	>2·2	>78·0
				$0·0\pm0·03$ ($J=4$)			>3·3	>110·0
			3·303(2^+)		20 ± 7			
			4·688(4^+)		20 ± 7			
			4·874(3^+)		5 ± 5			
6·830	2^-	2^-	0·0 (0^+)	E2		<67		
			4·116(2^+)					
			4·623(3^-)					
6·864		2^+, 4^+	2·127(2^-)	$-2·2\pm0·5$ ($J=2$)		70 ± 50	$0·73\pm0·28$	$23·0\pm9·0$
				$0·0\pm0·04$ ($J=4$)			$0·88\pm0·37$	$28·0\pm11·0$
			4·688(4^+)					
6·950	($\leqslant 4^+$)	2^+	3·303(2^+)					
			4·892(2^+)	$0·0\pm0·5$				
7·112	2^+ or 3^-	2^+	0·0 (0^+)	E2	8 ± 6	<10		
			2·127(2^+)	$-0·27^{+0·15}_{-0·19}$ or $-1·2^{+0·4}_{-0·7}$	66 ± 7			
			3·303(2^+)		26 ± 7			
7·220	($\leqslant 4^+$)	2^+	0·0 (0^+)	E2				
			4·688(4^+)			<18		
7·245			5·689(5^-)					

† Greene *et al* (1970).

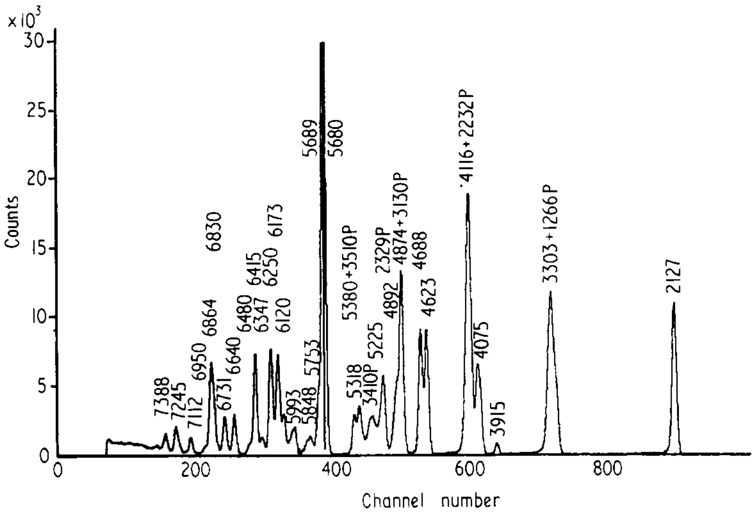

Figure 1. Spectrum of particles from alpha particle bombardment of ^{31}P target at $E_\alpha = 9{\cdot}3$ MeV, observed with the annular detector in coincidence with all gamma rays. The states in ^{34}S are denoted by their excitation energies in keV. States of ^{31}P are denoted by their excitation energy followed by the letter P.

or $\delta < -2{\cdot}4$ using the $J = 2$ assignment for the 5·680 MeV level determined earlier. The lifetime measurement of 380 ± 30 fs (Greene *et al* 1970 and private communication) enables one to calculate transition strengths (table 2) but these do not allow one to favour positive or negative parity for the level.

The five Ge(Li) crystal angular correlations experiment performed at $E_\alpha = 9{\cdot}3$ MeV allowed correlations to be extracted for the 1·001 MeV and 1·065 MeV primary decays from the 5·689 MeV level together with the 1·320 MeV secondary transition from the 4·623 MeV to the 3·303 MeV level. The low efficiency of the Ge(Li) detectors and the limited running time allowed only rather poor statistics to be accumulated for the three correlations. Simultaneous fits were made to the correlations of the 1·065 and 1·320 MeV transitions for spin hypotheses $1 \leqslant J \leqslant 6$ with the multipole mixing ratio of the 1·320 MeV transition fixed at the previously measured value of 0·03 (Mulhern *et al* 1971). Minimum χ^2 values of 5·8, 5·8, 2·6, 6·2, 2·1 and 10·3 were obtained for spin hypotheses $J = 1, 2, 3, 4, 5$ and 6 respectively, only $J = 3$ and $J = 5$ could not be ruled out at the 0·1 % confidence limit.

The 1·001 MeV, 1·065 MeV and 1·320 MeV correlations were then fitted simultaneously for spin hypotheses $J = 3$ and $J = 5$ and minimum χ^2 values of 3·29 and 2·86 respectively were obtained. As the 0·1 % confidence level is at $\chi^2 = 2{\cdot}96$ for the case considered here it is clearly difficult to rule out the $J = 3$ hypothesis on this basis alone.

However, a recent polarization direction correlation measurement by Greene *et al* (1971) resulted in an unambiguous assignment of $J^\pi = 5^-$ for the 5·689 MeV level. Using $J^\pi = 5^-$ we obtain a multipole mixing ratio of $\delta(\mathrm{M2/E1}) = 0{\cdot}05 \pm 0{\cdot}09$ for the 1·001 MeV transition to the 4·688 MeV level and a pure E2 transition for the 1·065 MeV transition to the 4·623 MeV level. These results are in good agreement with those of Greene *et al* (1971) who obtained $\delta(\mathrm{M2/E1}) = 0{\cdot}0 \pm 0{\cdot}02$ and pure E2 respectively.

Figure 4 shows the best fits to the Ge(Li) correlations of the 1·001, 1·065 and 1·320 MeV transitions for the $J = 3$ and $J = 5$ hypotheses. It is clear that better statistics

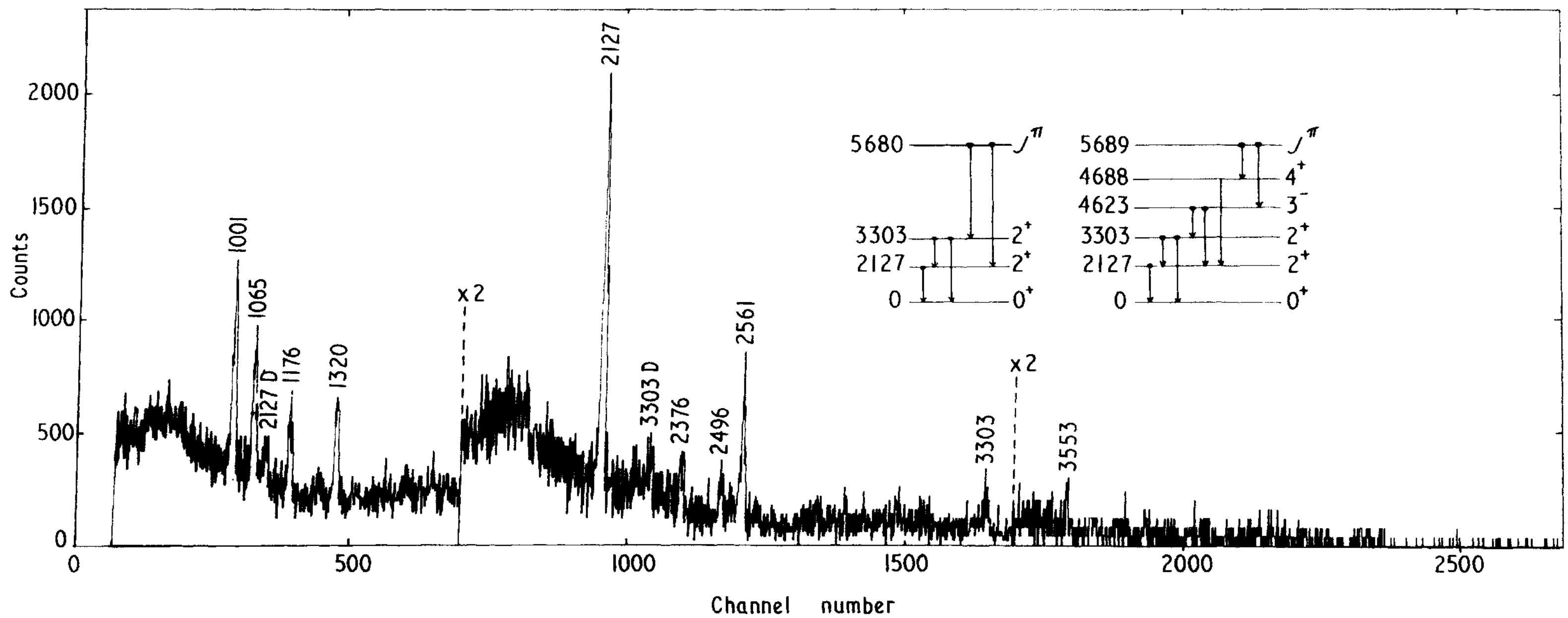

Figure 2. Spectrum of γ rays observed in Ge(Li) detector at $E_\alpha = 9{\cdot}3$ MeV in coincidence with proton groups corresponding to population of the 5·680 and 5·689 MeV levels. E_γ is expressed in keV and double escape peaks are labelled by the letter D.

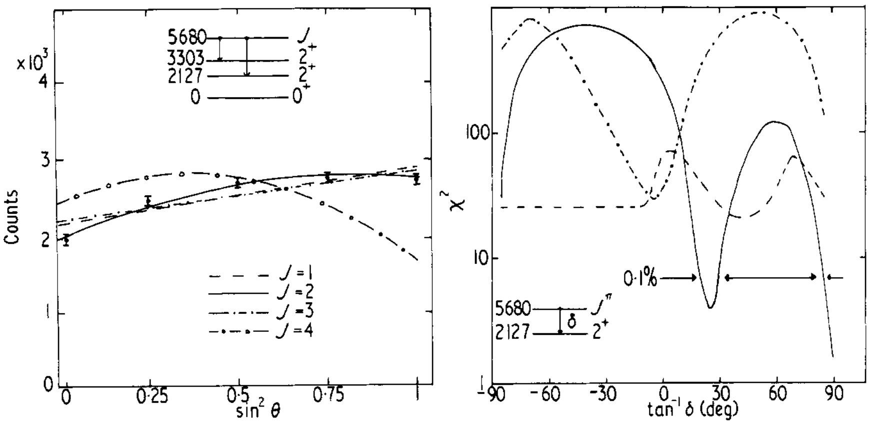

Figure 3. Experimental correlation of the 3·553 MeV transition and least squares fits for spin hypotheses $J = 1, 2, 3$ and 4 for the 5·680 MeV level together with the resulting χ^2 plots.

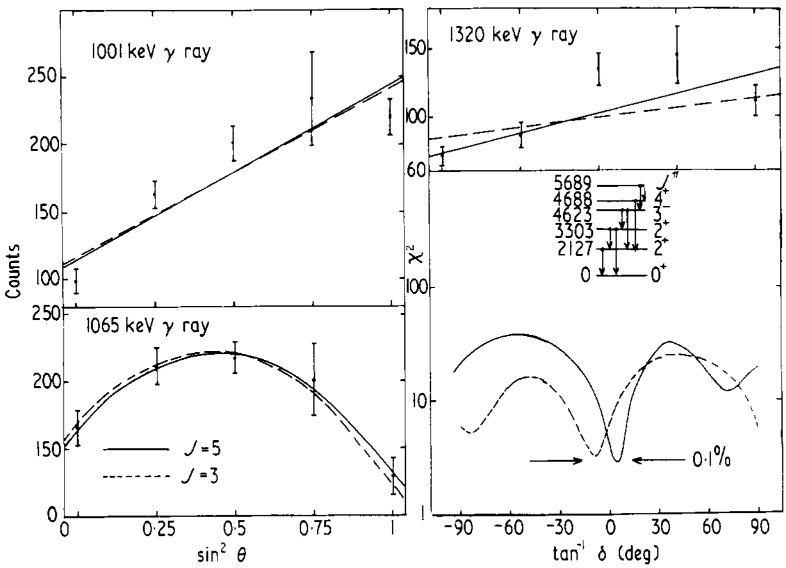

Figure 4. Experimental correlations obtained with five Ge(Li) detectors of the 1·001, 1·065 and 1·320 MeV transitions and least squares fits for spin hypotheses $J = 3, 5$ for the 5·689 MeV level together with the resulting χ^2 plots for the 1·001 MeV gamma ray.

for the secondary 1·320 MeV correlation would have greatly enhanced the prospects of obtaining a unique spin assignment by the present method.

3.2. The 5·753 and 5·848 MeV levels

Although the 5·753 MeV level was more strongly excited at $E_\alpha = 9{\cdot}3$ MeV than at $E_\alpha = 11{\cdot}0$ MeV it was not possible to resolve it completely in the particle spectrum from the 5·689 MeV level. The coincidence Ge(Li) spectrum revealed γ rays of energy 3·626 MeV from a cascade through the 2·127 MeV level but these γ rays could not be resolved in the NaI(Tl) detectors from the 3·553 MeV transition due to the decay of the 5·680 MeV level. The 5·753 MeV level has previously been assigned $J^\pi = 1^-$ (Hinds 1965 private communication) by the $^{32}S(t, p)^{34}S$ reaction and the decay modes through the first and second excited 2^+ states are consistent with this assignment.

The 5·848 MeV level was only weakly excited at $E_\alpha = 9·3$ and 11·0 MeV. However, the sum of coincidence spectra from all five NaI(Tl) spectrometers showed evidence of a 3·721 MeV transition through the 2·127 MeV level. This level has been assigned $J^\pi = 0^+$ (Hinds 1965 private communication) from the $^{32}S(t, p)^{34}S$ reaction.

3.3. *The 5·993 MeV level*

This well resolved level (figure 1) was observed to decay by a $55 \pm 10\,\%$ branch to the ground state (0^+), $25 \pm 8\,\%$ through the 2·127 MeV (2^+) level and $20 \pm 8\,\%$ through the 4·075 MeV (1^+) level. The correlation obtained from the transition to ground yielded minimum χ^2 values of 158·1, 2·1, and 187·9 for spin hypotheses $J = 1, 2$ and 3 respectively. Both $J = 1$ and $J = 3$ were rejected at the 0·1 % confidence level, confirming the spin in the $J^\pi = 2^+$ assignment from the $^{32}S(t, p)^{34}S$ reaction (Hinds 1965 private communication). The lifetime of the level was measured to be less than 10 fs (Greene *et al* 1970 and private communication) confirming the positive parity assignment from transition rate considerations (table 2) in this mass region (Skorka *et al* 1966).

Correlations could not be extracted for the 1·918 MeV and 3·866 MeV primary transitions owing to the proximity of γ rays in the spectra from subsequent decays.

3.4. *The 6·120 MeV and 6·173 MeV levels*

Narrow windows were set on this region of the particle spectrum so that γ rays from the decay of the 6·173 MeV level were not observed in the γ ray spectrum of the 6·120 MeV level and vice versa. The Ge(Li) coincidence spectrum revealed that the 6·120 MeV level decays through the 3·303 MeV (2^+) and 2·127 MeV (2^+) levels while the 6·173 MeV level decays through the 4·892 (2^+), 4·688 (4^+), 3·303 (2^+) and 2·127 MeV (2^+) levels. Figure 5 shows the NaI(Tl) spectra obtained from the narrow window settings together with decay schemes.

The correlations of the 2·817 and 3·303 MeV cascade transitions from the decay of the 6·120 MeV level were fitted simultaneously and yielded minimum χ^2 values of 2·4, 3·2, 11·9 and 63·4 for spin hypotheses $J = 1, 2, 3$ and 4 respectively. Both $J = 3$ and $J = 4$ were rejected at the 0·1 % confidence limit and the present work does not enable either $J = 1$ or 2 to be preferred. However, $J^\pi = 2^+$ has been assigned to this level on the basis of the $^{32}S(t, p)^{34}S$ reaction (Hinds 1965 private communication) and with $J^\pi = 2^+$ the present work gives a multipole mixing ratio for the 2·817 MeV transition of $\delta(E2/M1) = 0·09 \pm 0·04$. No reliable correlation could be obtained for the 3·993 MeV transition to the 2·127 MeV level owing to poor statistics for this decay mode.

The spin of the 6·173 MeV level was obtained by fitting the correlations of the 2·870 and 3·303 MeV cascade transitions simultaneously. Minimum χ^2 values of 14·1, 3·1 and 109·2 were obtained for spin hypotheses $J = 2, 3$ and 4 respectively. Both $J = 2$ and $J = 4$ were rejected at the 0·1 % confidence limit and for $J = 3$ two solutions are possible for the multipole mixing ratio of the 2·870 MeV transition either $\delta = 0·23 \pm 0·07$ or $\delta = 1·9 \pm 0·6$. The lifetime of the 6·173 MeV level was measured (Greene *et al* 1970 and private communication) to be less than 13 fs and transition

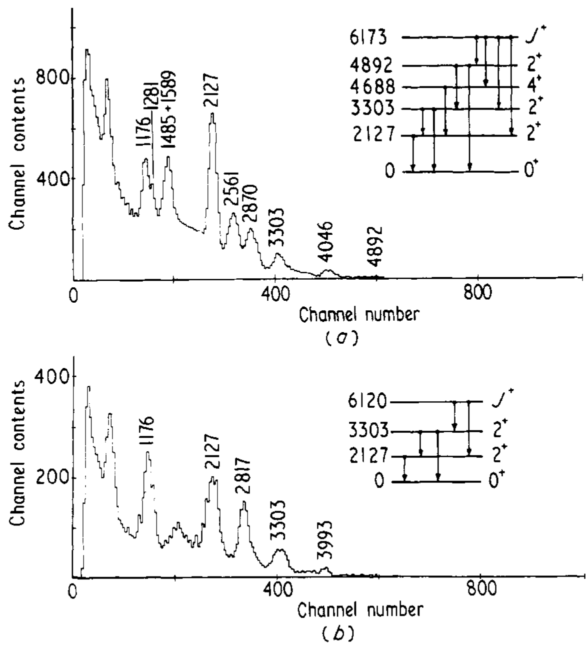

Figure 5. Gamma ray spectrum in coincidence with protons from (*a*) the 6·120 MeV level and (*b*) the 6·173 MeV level. It may be noted that the narrow proton window settings did not permit γ rays from the decay of one level to appear in the other spectrum.

strength considerations (table 2) using the tables of Skorka *et al* (1966) indicate positive parity with the multipole mixing ratio of $\delta = 0{\cdot}23 \pm 0{\cdot}07$ the more probable of the two possible solutions.

The multipole mixing ratio of the 1·485 MeV transition from the 6·173 MeV (3^+) level to the 4·688 MeV (4^+) level was obtained by simultaneously fitting the correlations of the 1·485, 2·870 and 3·303 MeV transitions with the multipole mixing ratio of the 2·870 MeV transition fixed at its most probable value $\delta = 0{\cdot}23$. The multipole mixing ratio obtained for the 1·485 MeV transition was $\delta(\mathrm{E2/M1}) = -0{\cdot}04^{+0{\cdot}03}_{-0{\cdot}06}$.

The multipole mixing ratio of the 4·046 MeV transition to the 2·127 MeV (2^+) level was obtained by simultaneously fitting the correlations of the 4·046, 2·870 and 3·303 MeV transitions yielding $\delta(\mathrm{E2/M1}) = 0{\cdot}43 \pm 0{\cdot}16$ or $1{\cdot}0 \pm 0{\cdot}3$.

No correlations could be extracted for the 1·589 MeV transition to the 4·892 MeV level due to the poor statistics and the proximity of the 1·485 MeV γ ray.

3.5. The 6·250 MeV level

Narrow windows were set on the particle spectrum to avoid contamination of the 6·250 MeV γ ray spectrum with γ rays from the 6·173 MeV level.

The 6·250 MeV level decays through the 4·874 MeV (3^+) and 4·688 MeV (4^+) states with γ rays of 1·376 MeV and 1·562 MeV. The correlation of the 1·376 MeV γ ray was fitted with minimum χ^2 values of 24·6, 39·7, 1·2 and 82·5 for spin hypotheses $J = 2, 3, 4$ and 5 respectively, the fits being shown in figure 6. Only $J = 4$ could not be rejected at the 0·1 % confidence limit. The multipole mixing ratio obtained for the 1·376 MeV

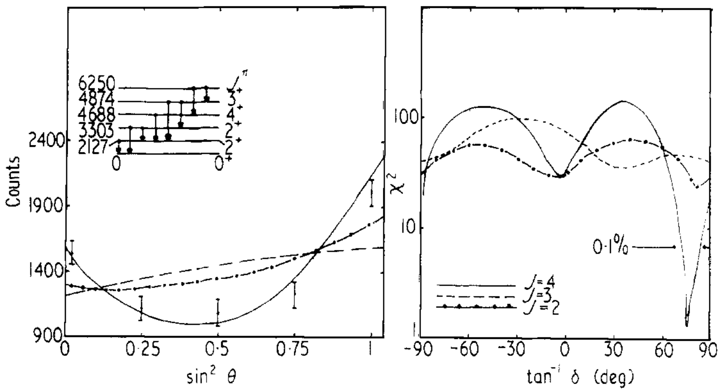

Figure 6. Experimental correlation of the 1·376 MeV transition and least squares fits for spin hypotheses J = 2, 3 and 4 for the 6·250 MeV level together with the resulting χ^2 plots.

transition was $\delta = 3{\cdot}7^{+2\cdot6}_{-0\cdot7}$ and the measured lifetime of 390^{+70}_{-40} fs (Greene *et al* 1970 and private communication) implies an E2 transition strength of 19 ± 4 Wu if the 4·874 and 6·250 MeV states are both of the same parity and an M2 transition strength of 600 ± 100 Wu if the levels are of opposite parity. The tabulation of Skorka *et al* (1966) implies that the 4·874 and 6·250 MeV levels have the same parity and since Puttaswamy and Yntema (1969) find evidence of positive parity for the 6·250 MeV level, we obtain $J^\pi = 3^+$ for the 4·874 MeV level and $J^\pi = 4^+$ for the 6·250 MeV level. The correlation of the 1·562 MeV γ ray from the 6·250 MeV level could not be extracted as it was degenerate in the NaI(Tl) spectra with the 1·571 MeV γ ray from the subsequent decay of the 4·874 MeV level to the 3·303 MeV level.

3.6. *The 6·347 MeV level*

The coincidence Ge(Li) spectrum revealed decays to ground and through the 3·303 MeV (2^+) level. Minimum χ^2 values obtained by fitting the 6·347 MeV to ground transition were 0·3, 12·8 and 54·6 for spin hypotheses of J = 1, 2 and 3 respectively. Both J = 2 and 3 could be rejected at the 0·1 % confidence limit.

The multipole mixing ratio of the 3·044 MeV transition to the 3·303 MeV level was obtained by simultaneously fitting the correlations of the degenerate (3·044 + 3·303 MeV) γ rays and the correlation of the 6·347 MeV γ ray using a grid search program. The plot of χ^2 against $\tan^{-1}\delta$ for the $J = 1$ hypothesis was found to be largely insensitive to changes in the multipole mixing ratio of the 3·044 MeV transition; the minimum spanning the range $-0{\cdot}1 \leqslant \delta \leqslant 1{\cdot}2$. Hinds (1965 private communication) obtained $J^\pi = 1^-$ for the 6·347 MeV level using the $^{32}S(t, p)^{34}S$ reaction.

3.7. *The 6·415 MeV level*

This level was strongly excited at E_α = 9·3 MeV, the Ge(Li) coincidence spectrum revealing a 1·541 MeV transition to the 4·874 MeV (3^+) level and a 1·727 MeV transition to the 4·688 MeV (4^+) level. The 1·541 MeV transition could not be resolved in the NaI(Tl) detectors from the 1·571 MeV transition from the decay of the 4·874 MeV level. A grid search analysis was carried out keeping δ = 0·09 fixed for the 1·571 MeV transition (Mulhern *et al* 1971). The observed decay modes limit the spin of the 6·415 MeV level to $2 \leqslant J \leqslant 5$. Minimum χ^2 values for spin hypotheses $J = 2, 3, 4$ and 5 were 2·7, 6·3, 2·8 and 91 respectively. Both $J = 3$ and $J = 5$ could be rejected at the 0·1% confidence limit. Figure 7 shows the best fits to the correlations using the grid search analysis.

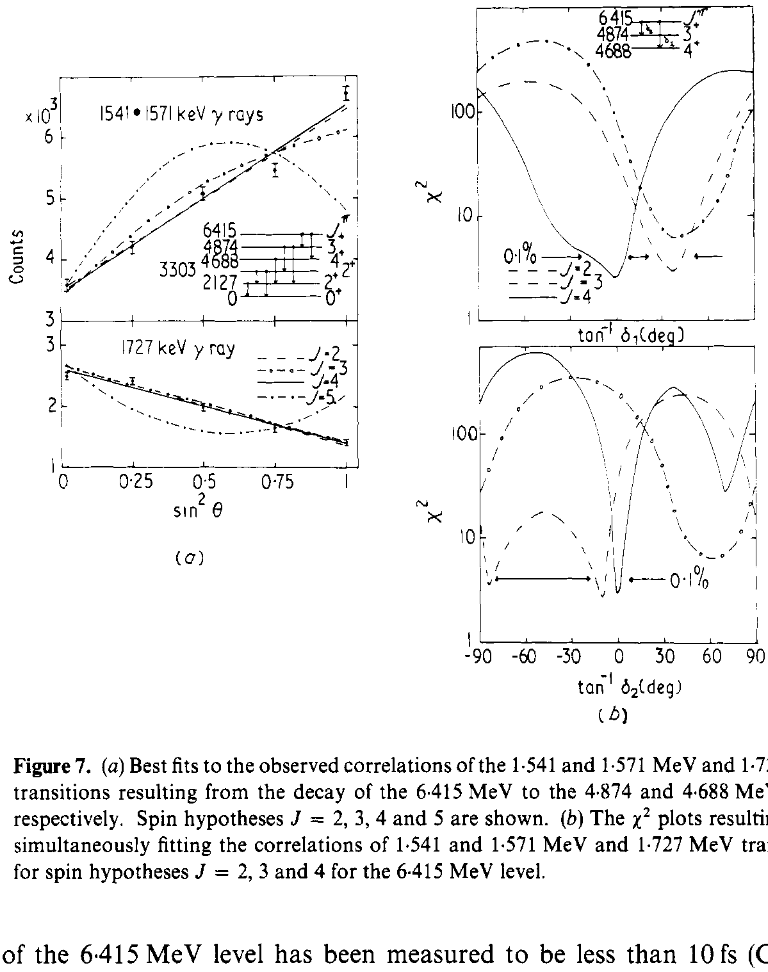

Figure 7. (*a*) Best fits to the observed correlations of the 1·541 and 1·571 MeV and 1·727 MeV transitions resulting from the decay of the 6·415 MeV to the 4·874 and 4·688 MeV levels respectively. Spin hypotheses $J = 2$, 3, 4 and 5 are shown. (*b*) The χ^2 plots resulting from simultaneously fitting the correlations of 1·541 and 1·571 MeV and 1·727 MeV transitions for spin hypotheses $J = 2$, 3 and 4 for the 6·415 MeV level.

The lifetime of the 6·415 MeV level has been measured to be less than 10 fs (Greene *et al* 1970 and private communication). The $J = 2$ hypothesis yielded a multipole mixing ratio of $\delta = 0{\cdot}58 \pm 0{\cdot}20$ for the 1·727 MeV transition which implies an E2 transition strength greater than 39 Wu for a positive parity state and an M2 transition strength greater than 1000 Wu for a negative parity state. Since both these transition strengths are outside the normal range of transition strengths in this mass region (Skorka *et al* 1966) $J = 2$ is unlikely for this state. The $J = 4$ hypothesis yielded a multipole mixing ratio of $\delta = 0{\cdot}0^{+0{\cdot}14}_{-0{\cdot}32}$ for the 1·727 MeV transition and $\delta = 0{\cdot}0 \pm 0{\cdot}06$ for the 1·541 MeV transition to the 4·874 MeV level.

3.8. The 6·480 MeV and 6·530 MeV levels

The 6·480 MeV level decays via a 3·177 MeV γ ray through the 3·303 MeV (2^+) level and a 4·353 MeV γ ray through the 2·127 MeV (2^+) level. The correlations of the 4·353 MeV, 1·176 MeV and 2·127 MeV γ rays were fitted simultaneously since the

3·177 MeV and 3·303 MeV γ rays could not be resolved in the NaI(Tl) spectra. Minimum χ^2 values of 6·5, 2·9, 14·6, 54·2 and 27·7 were obtained for spin hypotheses $J = 0, 1, 2, 3$ and 4 respectively. Only $J = 1$ could not be rejected at the 0·1 % confidence limit. The multipole mixing ratio for the 3·177 MeV transition was determined to be pure quadrupole while the multipole mixing ratio for the 4·353 MeV transition was found to be $0{\cdot}19 \leqslant \delta \leqslant 2{\cdot}0$.

No evidence was obtained for the excitation of a level previously observed at 6·530 MeV (Hinds 1965 private communication).

3.9. The 6·640 MeV level

This level was found to decay by means of branches through the 5·680 MeV (2^-) and 4·623 MeV (3^-) levels. The 2·017 MeV transition to the 4·523 MeV level was not resolved in the NaI(Tl) detectors from the 2·127 MeV transition arising from the subsequent decay of the first excited state to ground. It was also impossible to extract a reliable correlation for the 960 keV transition to the 5·680 MeV level. However, the presence of nonzero a_4 Legendre polynomial coefficients for several angular correlations from this level indicates that the spin of the level is unlikely to be 1 (table 1). Thus the spin of the level probably lies in the range $2 \leqslant J \leqslant 4$.

3.10. The 6·731 MeV level

The Ge(Li) coincidence spectrum revealed that the major decay mode was via a 4·046 MeV transition to the 2·127 MeV (2^+) level. Further decay modes were observed via the 3·303 MeV (2^+), 4·688 (4^+) and 4·874 MeV (3^+) levels. The only γ ray correlation which could be extracted from the NaI(Tl) spectra was for the 4·046 MeV major decay mode. Minimum χ^2 values of 1·1, 73·7 and 1·1 were obtained for spin hypotheses $J = 2, 3$ and 4 respectively. The $J = 3$ hypothesis was rejected by the 0·1 % confidence limit. The $J = 2$ hypothesis yielded a multipole mixing ratio of $\delta = -1{\cdot}8 \pm 0{\cdot}3$ while $J = 4$ yielded $\delta = 0{\cdot}00 \pm 0{\cdot}03$ for the 4·046 MeV transition. The lifetime was measured (Greene *et al* 1970 and private communication) to be less than 10 fs and transition rate considerations (Skorka *et al* 1966) indicate positive parity for the level with $J = 2$ or 4 allowed (table 2).

3.11. The 6·830, 6·864 and 6·898 MeV levels

These levels could not be resolved in the particle detector (figure 1) and it was necessary to set several narrow windows over the composite particle peak in order to establish the major decay modes. The 6·830 MeV level was found to decay directly to ground, to the 4·116 MeV (2^+) level and to the 4·623 MeV (3^-) level. The correlation of the direct transition to ground yielded minimum χ^2 values of 11·6, 2·1 and 22·1 for spin hypotheses $J = 1, 2$ and 3 respectively. Both $J = 1$ and $J = 3$ were rejected at the 0·1 % confidence level. The $J = 2$ assignment verifies the spin of a previous $J^\pi = 2^+$ assignment (Hinds 1965 private communication). Neither angular correlations nor branching ratios could be obtained for the other transitions from the 6·830 MeV level owing to the weakness of excitation together with the complexity of the coincidence spectra.

The major decay of the 6·864 MeV level was a 4·737 MeV transition through the 2·127 MeV level. Minimum χ^2 values of 273·5, 134·2, 3·5, 30·8 and 4·0 were obtained for spin hypotheses of $J = 0, 1, 2, 3$ and 4 respectively. Only $J = 2$ and $J = 4$ could not be rejected at the 0·1 % confidence level. The mixing ratio obtained for the $J = 2$ hypothesis was $\delta = -2{\cdot}2 \pm 0{\cdot}5$ and for the $J = 4$ hypothesis $\delta = 0{\cdot}0 \pm 0{\cdot}04$.

Transition rate considerations (table 2) using the lifetime measurement (Greene *et al* 1970 and private communication) of 70±50 fs indicate positive parity for the level.

It was not possible to extract any correlations from the decay of the 6·898 MeV level because of the weakness of excitation and contamination from neighbouring levels.

3.12. The 6·950 MeV level

This level decays through the 4·892 MeV (2^+) and 3·303 MeV (2^+) levels. The primary 2·058 MeV decay could not be resolved in the NaI(Tl) detectors from the 2·127 MeV transitions arising from the subsequent decay of the first excited state and the primary 3·647 MeV transition could only be partially resolved from the subsequent 3·303 MeV transition. The 2·058 MeV γ ray was therefore treated as an unobserved transition and the correlation of the secondary 4·892 MeV transition was fitted for different spin hypotheses for the 6·950 MeV level, the 4·892 MeV transition being pure E2 (Mulhern *et al* 1971). Minimum χ^2 values of 13·2, 24·7, 0·4, 20·3 and 21·5 were found for spin hypotheses $J = 0, 1, 2, 3$ and 4 the fits and χ^2 plots being shown in figure 8. The hypotheses $J = 0$, 1, 3 and 4 were rejected at the 0·1 % confidence limit. The multipole mixing ratio obtained for the 2·058 MeV transition with the $J = 2$ hypothesis was $\delta = 0{\cdot}0 \pm 0{\cdot}5$.

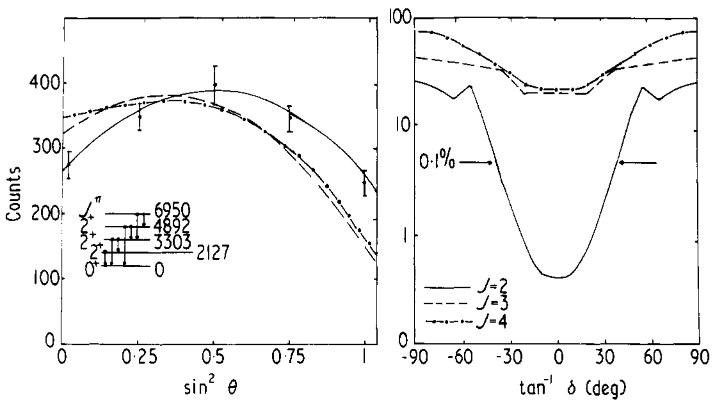

Figure 8. The experimental correlation of the 4·892 MeV transition with best fits for spin hypotheses $J = 2$, 3 and 4 for the 6·950 MeV level plus the resulting χ^2 plots.

3.13. The 7·112 MeV level

The level was observed to decay directly to ground, and to the 2·127 (2^+) and 3·303 MeV (2^+) levels. Fits to the ground state transition yielded minimum χ^2 values of 24·5, 3·0 and 35·4 for $J = 1, 2$ and 3 respectively. Both $J = 1$ and $J = 3$ were ruled out at the 0·1 % confidence limit. The multipole mixing ratio of the 4·985 MeV transition to the 2·127 MeV level for the $J = 2$ assignment was obtained by performing a simultaneous fit to the correlations of the 4·985 and 7·112 MeV transitions, the results of the fitting procedure being shown in figure 9. Two solutions were obtained for the mixing ratio either $\delta = -0{\cdot}27^{+0{\cdot}15}_{-0{\cdot}19}$ or $\delta = -1{\cdot}2^{+0{\cdot}4}_{-0{\cdot}7}$.

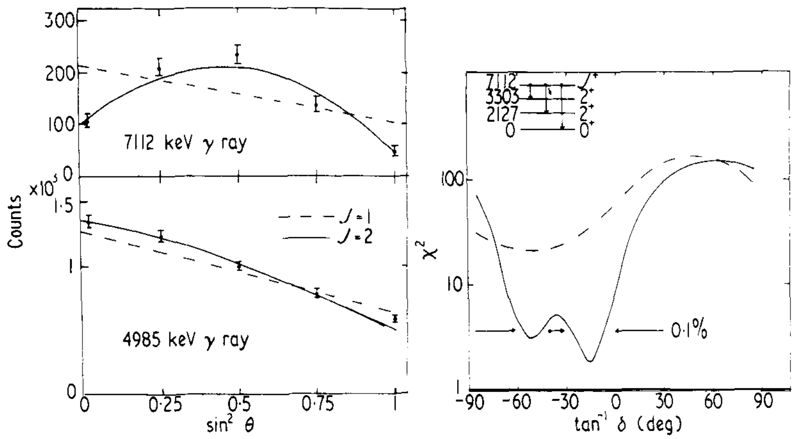

Figure 9. The observed correlation of the 4·985 and 7·112 MeV transitions and best fits for spin hypotheses $J = 1$ and 2 together with the χ^2 plots.

It was not possible to extract a reliable correlation for the 3·809 MeV transition to the 3·303 MeV level.

Hinds (1965 private communication) obtained $J^\pi = 2^+$ or 3^- for this level from the $^{32}S(t, p)^{34}S$ reaction.

3.14. The 7·220 and 7·245 MeV levels

Only one level had previously been observed in this region of excitation. The procedure of stepping across particle peaks with narrow window settings revealed two dissimilar spectra, shown in figure 10, for γ rays in coincidence with the high energy and low energy side of the composite particle peak. The NaI(Tl) spectra of figure 10 together with Ge(Li) coincidence data led to the decay schemes also shown in figure 10. Minimum χ^2 values obtained by fitting the correlation of the direct 7·220 MeV transition to ground were 27, 1·8 and 40·7 for spin hypotheses $J = 1, 2$ and 3 respectively. Only $J = 2$ is acceptable at the 0·1 % confidence limit (figure 11) and the rather unusual fact that the level decays both to ground (0^+) and to the 4·688 MeV (4^+) level together with a measured lifetime (Greene *et al* 1970 and private communication) of less than 18 fs suggests that $J^\pi = 2^+$ for the level. A level at $7{\cdot}19 \pm 0{\cdot}04$ MeV was assigned $J^\pi \leqslant 4^+$ in the work of Puttaswamy and Yntema (1969).

The 7·245 MeV level was found to decay predominantly to the 5·689 MeV (5^-) level and an attempt was made to obtain a correlation for the 1·556 MeV primary transition. However, the large errors involved in extracting the data led to inconclusive results for the spin of the 7·245 MeV level.

4. Discussion

The primary aim of the present work in determining spins, parities and mixing ratios for ^{34}S in the region from 5·4 MeV to 7·4 MeV is to provide a basis for a further extension of the shell model calculations of Glaudemans *et al* (1971). These shell model calculations have to date proved very successful in explaining most of the features of the low lying

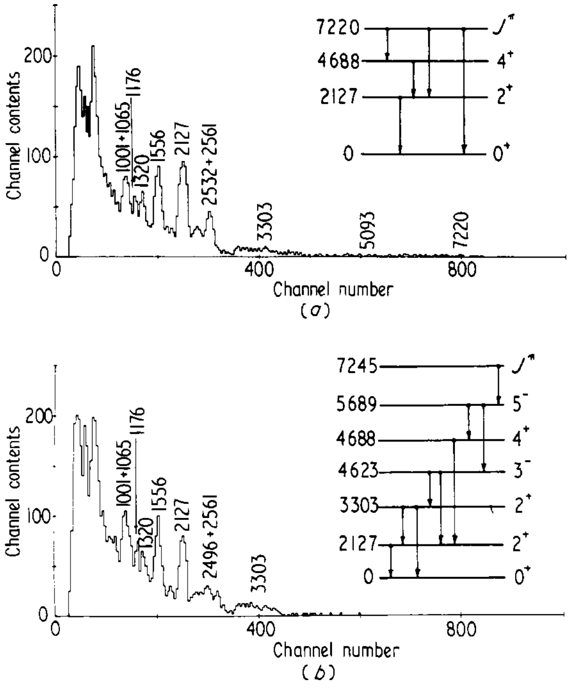

Figure 10. Gamma ray spectrum in coincidence with protons from (*a*) the 7·220 MeV level and (*b*) the 7·245 MeV level.

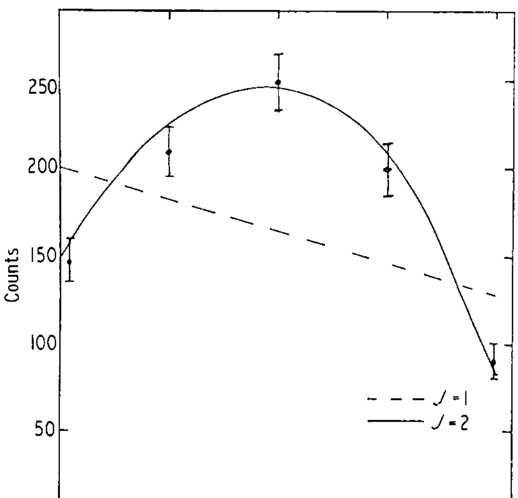

Figure 11. The observed correlation of the 7·220 MeV transition and best fits for spin hypotheses $J = 1$ and 2.

levels of ^{34}S (Mulhern *et al* 1971) and indeed in explaining many of the low lying levels of the nuclei in the 2s–1d shell.

Until the latest shell model calculations are completed for ^{34}S (Glaudemans 1971 private communication) it is perhaps instructive to examine the degree of success that the earlier calculations attain in explaining the level scheme up to an excitation energy of 7·4 MeV. The calculations were carried out with a model space chosen such that all $2s_{1/2}$ and $1d_{3/2}$ states and up to two holes in the $1d_{5/2}$ shell were taken into account. The modified surface delta interaction was taken as an effective two body interaction. Seven parameters were contained in the calculation—four describing the two body interaction and three the single particle energies. Figure 12 shows the theoretically calculated positive parity level scheme of ^{34}S calculated by the above method together with the experimentally observed level scheme of positive parity levels. Dashed lines join an experimental level and a theoretically predicted level lying close in energy. The many experimentally observed 2^+ levels have been omitted from the level scheme since the shell model calculations available to date only give positive information on the lowest four levels of any integral spin J^+ state. It may be noted from figure 12 that many of the higher excited states are predicted to be present from shell model calculations although as might be expected the level ordering is not quite so good as for the lower lying levels.

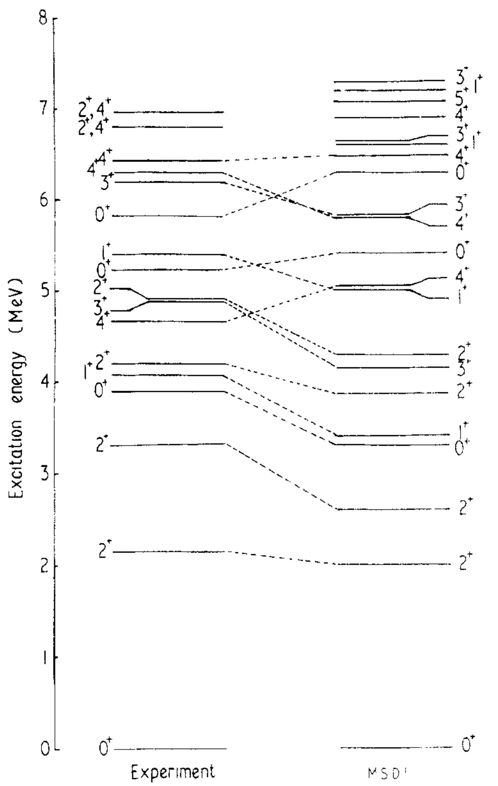

Figure 12. A comparison of the experimental level scheme of ^{34}S with the theoretically calculated level scheme of Glaudemans *et al* (1971) employing a modified surface delta interaction (MSDI) as an effective two body interaction for particles in the 2s–1d shells.

Although the shell model calculations of Glaudemans *et al* (1971) are quite capable of correctly predicting large E2 transition strengths for transitions in ^{34}S (Mulhern *et al* 1971) it is interesting to note an E2 transition strength of 19 ± 4 Wu from the 6·250 MeV (4^+) to the 4·874 MeV (3^+) level. Such an E2 transition strength is the largest found so far in the nucleus ^{34}S and is quite large for E2 transitions in the 2s–1d shell.

Little success has been achieved in the present work in identifying further negative parity states in ^{34}S. However, the 7·245 MeV level may be of interest in view of the observed decay through the 5·689 MeV (5^-) level and further experiments are proposed in order to study this level more thoroughly.

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