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Angular Correlation Measurements in ^{33}S

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Abstract

The $^{32}S(d, p)$ reaction has been used to excite states in ^{33}S. Proton–gamma angular correlations for states up to 4·43 MeV in excitation energy have been measured to determine spins and γ-ray branching and multipole mixing ratios. Results obtained for mixing ratios include $\delta(1\cdot97\to0) = 0\cdot75\pm0\cdot38$, $\delta(2\cdot93\to0) = 0\cdot19\pm0\cdot14$ and $\delta(2\cdot93\to1\cdot97) = 0\cdot00\pm0\cdot04$. Spin and parity assignments of $3/2^+$ and $(1/2^+, 3/2^\pm)$ have been found for the 3·94 and 4·43 MeV states respectively. Branching ratios have been determined for several previously unreported weak decays from high energy states.

Introduction

Shell model calculations for positive parity states in ^{33}S have been performed by Wildenthal *et al.* (1971) using configurations with active $1d_{5/2}$, $2s_{1/2}$ and $1d_{3/2}$ orbits. A maximum of two holes was allowed in the $d_{5/2}$ shell and a simple form of residual two-particle interaction was used, but agreement with much of the experimental data for low-lying states was nevertheless achieved. Castel *et al.* (1971) have also introduced an intermediate coupling model in which quasiparticles interact with an anharmonically vibrating ^{32}S core. A summary of experimental information on the nucleus has been compiled by Endt and van der Leun (1973). Formerly, few of the properties of the states above 3 MeV were known, but the successes of both models have stimulated further interest in this nucleus and these levels have recently been investigated by Hirko and Jones (1972), Carr *et al.* (1973), Butler *et al.* (1975) and Moalem and Wildenthal (1975). In the present study we have measured p–γ angular correlations from states in ^{33}S excited by the $^{32}S(d, p)$ reaction in order to investigate spins, branchings and mixing ratios. Fig. 1 shows a summary of results from this and previous studies.

Experimental Method

A beam of 3·5 MeV deuterons from the Auckland University folded tandem accelerator was used to bombard a thin target consisting of natural sulphur evaporated onto a carbon backing and covered with a thin layer of gold to prevent the evaporation of sulphur under bombardment. Protons were detected in an annular silicon surface barrier detector collimated to subtend angles between 166° and 173° to the beam direction and covered with a 7·5 μm aluminium foil to remove α-particle groups from regions of interest in the particle spectrum. Part of a typical spectrum of protons coincident with γ-rays of energies between 0·3 and 5·0 MeV is shown in

Fig. 2. A $12{\cdot}7 \times 15{\cdot}2$ cm NaI(Tl) crystal mounted 25 cm from the target was used to detect γ-rays.

Particle–γ coincidences were detected with a fast–slow coincidence system with a resolving time of $2\tau = 30$ ns. Coincident proton and γ-ray energy pulses and a signal identifying an event as falling within a 'real' or a 'random' coincidence timing window were digitized and stored on magnetic tape under the control of an on-line computer. Data were recorded with the γ-ray detector at angles of 21°, 30°, 45°, 60° and 90° to the beam, with runs at different angles taken in random order and each angle repeated several times.

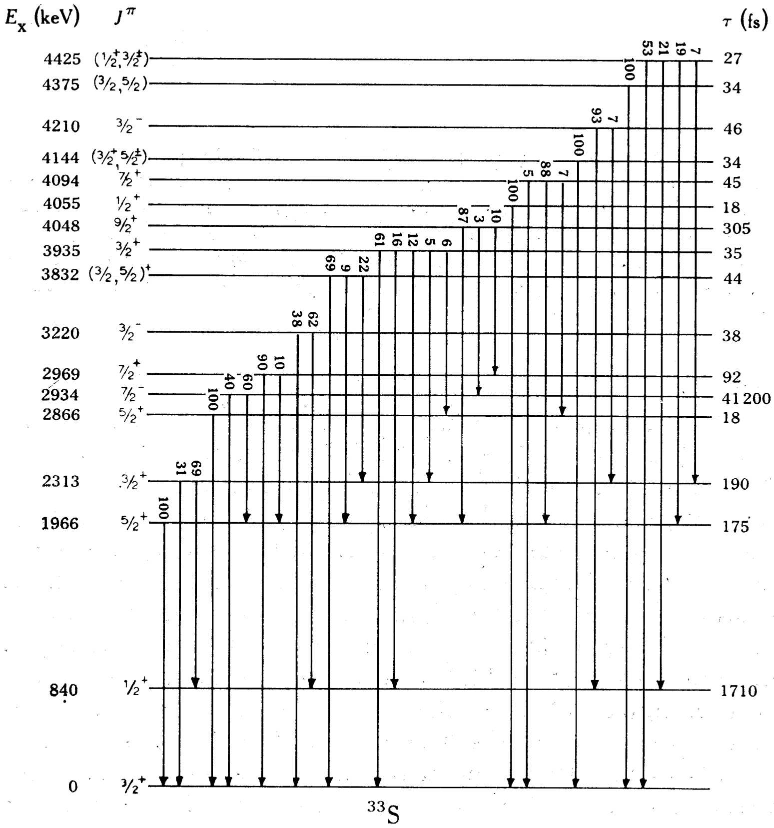


Fig. 1. Level scheme for ^{33}S. The data are from the Endt and van der Leun (1973) compilation, with additional results from Hirko and Jones (1972), Carr *et al.* (1973), Butler *et al.* (1975), Moalem and Wildenthal (1975) and the present investigation.

Analysis

The tapes were played back and the data from selected portions of the energy matrix summed to accumulate spectra of γ-rays in coincidence with proton groups from ^{33}S. Gains were kept fixed by a digital gain stabilizer in the playback code, which also subtracted the random coincidence contribution (typically 10% of the counts in peaks of interest). Figs 3*a* and 3*b* show the final spectra summed over all angles for two of the states. Peak areas from the spectra were normalized to the yield of the γ-ray from the spin 1/2 state (Endt and van der Leun 1973) at 0·84 MeV and the data from the different runs at each angle were averaged to produce final distributions, two of which are shown in Figs 4 and 5.

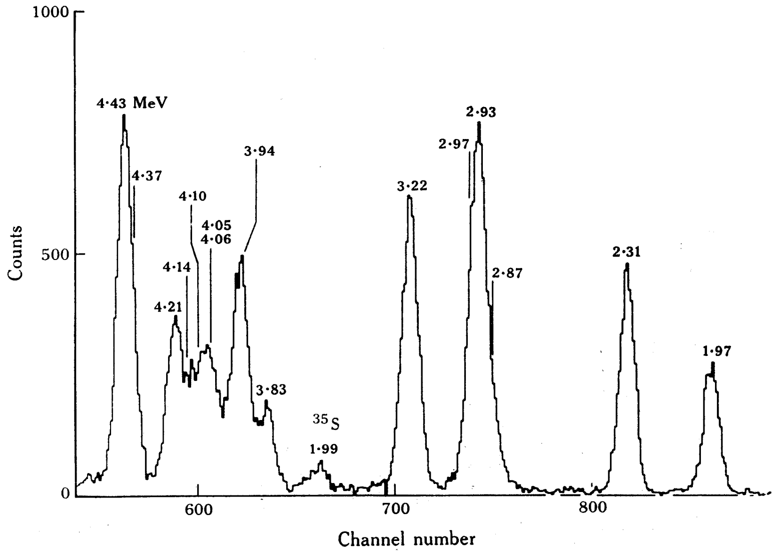


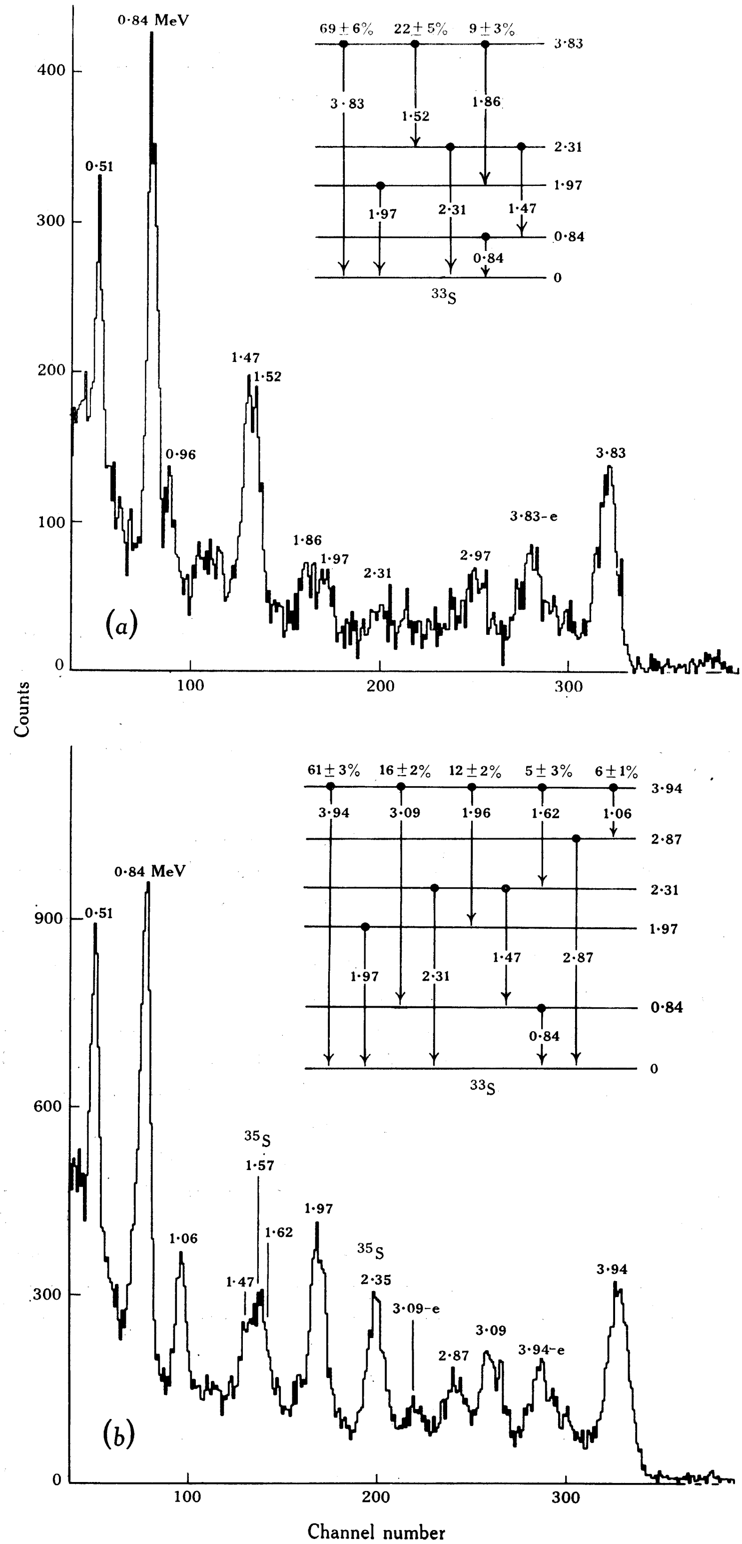
Fig. 2. Part of a typical spectrum of coincident particles in the reaction $^{32}S(d,p)^{33}S$ from one of the experimental runs ($E_d = 3\cdot50$ MeV, $\theta_p = 170°$), showing proton groups corresponding to states in ^{33}S.

Theoretical correlation formulae derived by Rose and Brink (1967) were fitted to the data to determine possible values for the mixing ratio δ for each transition of interest and the spins J_i and J_f of the corresponding initial and final states. Values were assumed for J_i and J_f and fits were made at 1° intervals in the range $-90° < \arctan\delta < 90°$. The quality of the fit is indicated by a normalized χ^2 parameter, and regions where this fell below the 0·1% confidence level were taken as possible solutions. Figs 4 and 5 show plots of χ^2 versus $\arctan\delta$ for some of the transitions of interest. The phase convention for mixing ratios is that of Rose and Brink (1967) and error limits were taken at the 31·7% confidence level. The effects of non-ideal particle and γ-ray detector geometries have been calculated according to the standard techniques of Litherland and Ferguson (1961).

Branching ratios for strong decays were estimated using the A_0 coefficients from Legendre polynomial fits to the correlations. Weaker branches were found from peak areas in the coincidence spectra summed over all angles. The total detection efficiencies of Rutledge (1959) and photofractions from lineshapes generated by our detector were used to reduce these data to a set of branching ratios.

Results

Our results are summarized in Tables 1, 2 and 3 which show respectively the coefficients from fits of even-order Legendre polynomials to the γ-ray distributions, a summary of the results of the angular correlation analyses and the set of


0·84 MeV
0·51
1·47
1·52
0·96
1·86
1·97
2·31
2·97
3·83-e
3·83
(a)
69 ± 6%
22 ± 5%
9 ± 3%
3·83
1·52
1·86
2·31
1·97
2·31
1·47
0·84
0·84
0
^{33}S
Counts
0·84 MeV
0·51
1·06
^{35}S
1·57
1·62
1·47
1·97
^{35}S
2·35
3·09-e
3·09
2·87
3·94-e
3·94
(b)
61 ± 3%
16 ± 2%
12 ± 2%
5 ± 3%
6 ± 1%
3·94
3·09
1·96
1·62
1·06
2·87
2·31
1·97
1·47
2·87
0·84
0
^{33}S
Channel number

branching ratios we derive. In the following discussion of the results of individual levels, we have derived estimates of transition strengths using branching ratios from Table 3 together with lifetimes which are error-weighted means of data from the Endt and van der Leun (1973) compilation and the new results of Carr *et al.* (1973). The criteria of Endt and van der Leun (1974) have been used to define acceptable transition strengths.

1·97 MeV Level

Our best estimate for the value of the mixing ratio for the $1\cdot97 \rightarrow 0$ MeV transition is taken from the correlation analysis of the $2\cdot93 \rightarrow 1\cdot97 \rightarrow 0$ MeV cascade. Butler *et al.* (1975) observed a 7 ± 1 % branch from the 1·97 MeV level to the 0·84 MeV state but our spectra indicate an upper limit of 2% for this branching ratio.

2·31 MeV Level

A simultaneous analysis of the $2\cdot31 \rightarrow 0$ and $2\cdot31 \rightarrow 0\cdot84$ MeV distributions fixes the spin of this level as 3/2, consistent with the spin–parity of $3/2^+$ quoted in the Endt and van der Leun (1973) compilation. Disagreement exists between the values obtained by Butler *et al.* (1975) and by Cummings and Donahue (1970) for the mixing ratio for the $2\cdot31 \rightarrow 0$ MeV transition. Our results cannot resolve this discrepancy, but those of other groups (Hirko and Jones 1972; Toulemonde and Schultz 1972), although not definitive, support the findings of Butler *et al.*

2·87 MeV Level

A correlation analysis of the $2\cdot87 \rightarrow 0$ MeV transition, performed after residual contamination from γ-rays from the decay of the 2·93 MeV level had been subtracted, allowed all spins up to $J = 5/2$. Butler *et al.* (1975) recently found $J = 5/2$ for this level; our mixing ratio results for this spin are given in Table 2.

2·93 MeV Level

Endt and van der Leun (1973) give the spin and parity of this state as $7/2^-$. Our correlation analysis allows two possible values for the mixing ratio of the $2\cdot93 \rightarrow 0$ MeV transition for $J = 7/2$, but the larger of these corresponds to an E3 strength for this transition of 126 ± 16 Weisskopf units (W.u.) and hence can be rejected.

3·22 MeV Level

The simultaneous correlation analysis of the $3\cdot22 \rightarrow 0$ and $3\cdot22 \rightarrow 0\cdot84$ MeV transitions fixes the spin of this level as 3/2. The M2 enhancements implied by the known (Endt and van der Leun 1973) negative parity of the state are sufficiently large to exclude all but one of the values for each mixing ratio allowed by this analysis.

Fig. 3 (*opposite*). Spectra of coincident γ-rays from the decays of the (*a*) 3·83 MeV level and (*b*) 3·94 MeV level, representing the summation of data accumulated at all the γ-ray detector angles. In (*a*) the major decay modes of the level are shown but other minor branches probably exist (see text). In (*b*) peaks from ^{35}S arise from the interaction of the deuteron beam with a small percentage of ^{34}S occurring naturally in the target.

(*f*) 3·83 MeV Level

This level is not well excited (as Fig. 2 shows) but it is clear from the γ-ray spectrum in Fig. 3*a* that the decay scheme is more complex than the results of Hirko and Jones (1972) and Carr *et al.* (1973) suggest. The state decays to the ground, 1·97 and 2·31 MeV states; and the presence of peaks at 960 ± 20 and 2970 ± 20 keV and the over-abundance of the 840 keV component of the $2 \cdot 31 \to 0 \cdot 84 \to 0$ MeV cascade indicate that other weak branches exist. We could make no meaningful

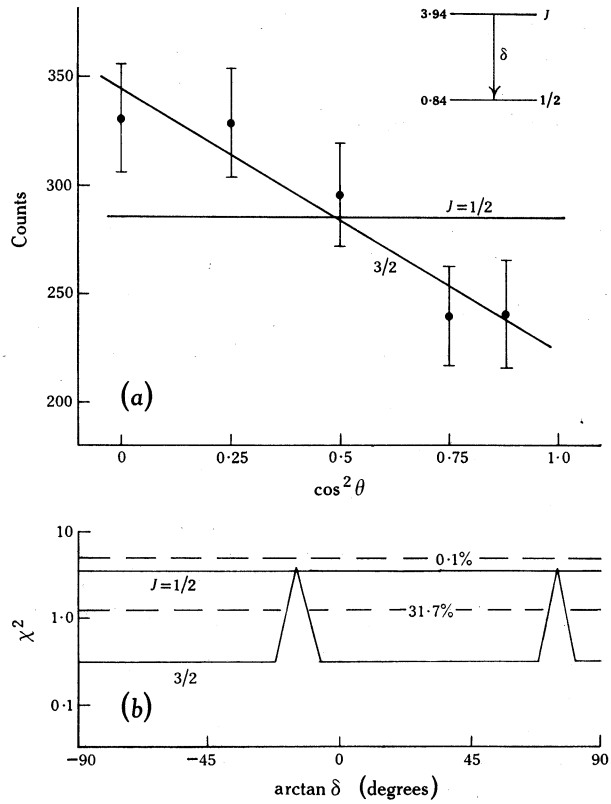


Fig. 4. Best fits to the data (*a*) and plots of χ^2 versus arctan δ (*b*) for the angular distribution from the $3 \cdot 94 \to 0 \cdot 84$ MeV transition in ^{33}S, shown for choices of initial spin which produced plots having $\chi^2_{min} < 10$. The probabilities of χ^2 exceeding the values indicated by the dashed lines if the theoretical distributions fitted describe the measured data accurately are 31·7% and 0·1% respectively as shown. The mixing ratio δ was taken equal to zero to generate the theoretical distribution shown for $J = 3/2$ in (*a*).

choice from among several possible minor decays and have simply indicated upper limits for these branches in Table 3. Solutions were obtained for $J = 3/2 - 7/2$ from the angular correlation analysis, while data from pickup reactions (Leighton and Wolff 1970; Moalem and Wildenthal 1975) require a spin–parity of $3/2^+$ or $5/2^+$ for the level. If the 16 ± 6 % branch to the 2·97 MeV state reported by Hirko and Jones (1972) does indeed exist, the E2 enhancement required for this transition for $J^{\pi} = 3/2^{+}$ is 970 ± 450 W.u. and the spin–parity of the level must be $5/2^{+}$. Our data suggest an upper limit of 11% for this branching ratio.

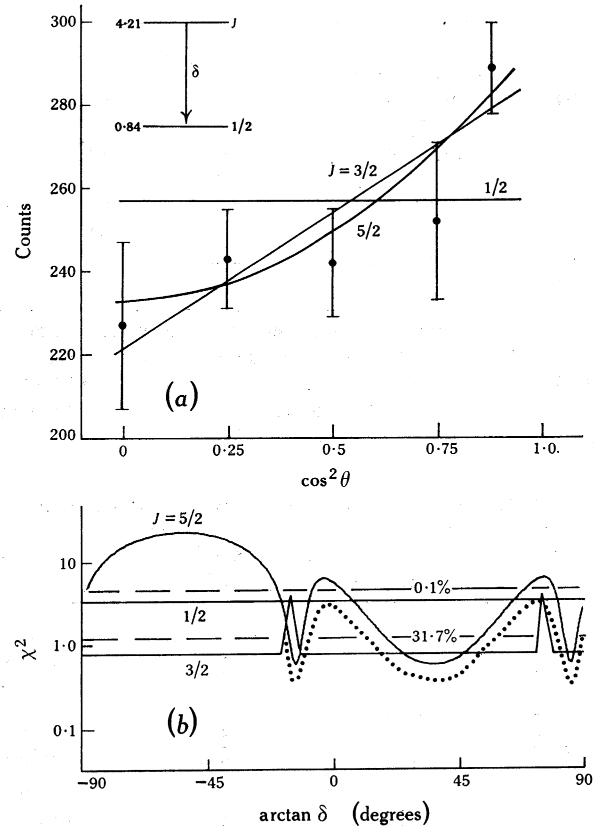


Fig. 5. Best fits (*a*) and plots of χ^2 versus arctan δ (*b*) for the angular distribution from the 4·21→0·84 MeV transition in ^{33}S. The effects of allowing for non-ideal particle detector geometry by permitting a 6% population of the $|m_z| = 5/2$ magnetic substate of the initial level are shown by the dotted curve. The values of δ assumed for the theoretical distributions in (*a*) for $J = 3/2$ and 5/2 are 0 and −0·25 respectively.

3·94 MeV Level

Fig. 3*b* shows that decays from this level to the 1·97, 2·31 and 2·87 MeV states exist in addition to the branches to the ground and 0·84 MeV states reported by Hirko and Jones (1972) and by Carr *et al.* (1973). The analysis of the 3·94→0 and 3·94→0·84 MeV transitions (see Fig. 4) allows $J = 1/2$ and 3/2, but the existence of a 6 ± 1 % branch to the $5/2^{+}$ state at 2·87 MeV and the lifetime of the state, as determined by Carr *et al.* (1973), would require E2 or M2 enhancements >100 W.u. for $J = 1/2$. Stripping and pickup reaction data (Leighton and Wolff 1970; Graue *et al.* 1971; Moalem and Wildenthal 1975) show that the spin–parity must be $3/2^{+}$ or $5/2^{+}$; combining all these data allows us to uniquely assign $J^{\pi} = 3/2^{+}$ to this level. The recent determination of the spin of this level by Butler *et al.* (1975) is therefore confirmed.

Table 1. Legendre polynomial coefficients

E_i (MeV)	E_f (MeV)	Coefficients[A] A_2/A_0	E_i (MeV)	E_f (MeV)	Coefficients[A] A_2/A_0
1·97	0	$-0·71\pm0·04$	3·94	0	$0·05\pm0·07$
2·31	0	$-0·03\pm0·03$	3·94	0·84	$-0·26\pm0·08$
2·31	0·84	$-0·19\pm0·02$	3·94	1·97 }[C]	$-0·06\pm0·07$
2·87	0	$-0·05\pm0·03$	1·97	0[B] }	
2·93	0	$0·21\pm0·05$	3·94	2·87	$0·05\pm0·10$
2·93	1·97	$-0·27\pm0·05$	4·21	0·84	$0·15\pm0·06$
1·97	0[B]	$-0·78\pm0·06$	4·43	0	$-0·03\pm0·04$
3·22	0	$0·07\pm0·03$	4·43	0·84	$-0·15\pm0·02$
3·22	0·84	$-0·09\pm0·03$	4·43	1·97	$-0·04\pm0·13$
3·83	0	$0·31\pm0·06$	1·97	0[B]	$-0·11\pm0·09$

[A] These coefficients have not been corrected for finite detector size. Values of A_4/A_0 coefficients obtained for the distributions were: $-0·06\pm0·05$, $-0·08\pm0·04$ and $0·09\pm0·08$ for the 3·22→0, 3·22→0·84 and 4·21→0·84 MeV transitions respectively. All other A_4/A_0 coefficients were zero to within experimental error.
[B] From cascade. [C] Unresolved transitions.

Table 2. Summary of angular correlation analysis results

$E_i \to E_f$ (MeV)	Spin of initial state J_i Tested	Possible solns	Result J_i^π	Mixing ratio δ
1·97→0	$\frac{3}{2}-\frac{9}{2}$	$\frac{5}{2}$[A]	$\frac{5}{2}^+$	$0·75\pm0·38$[A]
2·31→0	$\frac{3}{2}-\frac{7}{2}$	$\frac{3}{2}$	$\frac{3}{2}^+$	$0·38\pm0·25$, <-11, >3
2·31→0·84				$0·6^{+2·3}_{-0·8}$, $<-0·3$, >6
2·87→0	$\frac{1}{2}-\frac{7}{2}$	$\frac{1}{2}-\frac{5}{2}$	$\frac{5}{2}^+$	$-0·16^{+0·25}_{-0·05}$ or $7·1^{+4·3}_{-1·4}$
2·93→0	$\frac{3}{2}-\frac{9}{2}$	$\frac{3}{2}, \frac{7}{2}$	$\frac{7}{2}^-$	$0·19\pm0·14$
2·93→1·97				$0·00\pm0·04$
3·22→0	$\frac{1}{2}-\frac{7}{2}$	$\frac{3}{2}$	$\frac{3}{2}^-$	$-7<\delta<0·2$
3·22→0·84				$-0·2<\delta<2·5$
3·83→0	$\frac{3}{2}-\frac{9}{2}$	$\frac{3}{2}-\frac{7}{2}$	$(\frac{3}{2}^+)$	$-11<\delta<0·1$ or $0·5<\delta<6$
			$(\frac{5}{2}^+)$	-5^{+2}_{-6} or $0·4^{+0·1}_{-0·4}$
3·94→0·84	$\frac{1}{2}-\frac{7}{2}$	$\frac{1}{2}, \frac{3}{2}$	$\frac{3}{2}^+$	See Fig. 4
4·21→0·84	$\frac{1}{2}-\frac{7}{2}$	$\frac{1}{2}-\frac{5}{2}$	$\frac{3}{2}^-$	$-0·2<\delta<3$
4·43	$\frac{1}{2}-\frac{7}{2}$	$\frac{1}{2}-\frac{5}{2}$[B]	$(\frac{1}{2}^+, \frac{3}{2}^\pm)$[B]	

[A] From the analysis of the 2·93→1·97→0 MeV cascade.
[B] From the analysis of transitions to the 0 and 0·84 MeV levels and of the 4·43→1·97→0 MeV cascade.

4·21 MeV Level

The coincident γ-ray spectrum from this level contains evidence for the existence of a weak branch to the 2·31 MeV state. The correlation analysis of the major decay to the 0·84 MeV state allows $J = 3/2$ or $5/2$ (and $J = 1/2$ at the 1% confidence level). The mixing ratios from Fig. 5 would require E3 or M3 strengths >1000 W.u. for $J = 5/2$; our data therefore support the accepted spin–parity assignment of $J = 3/2^-$ for this level quoted by Endt and van der Leun (1973). Two of our three mixing ratio solutions for $J = 3/2$ can be rejected as they require M2 strengths >14 W.u.

Table 3. γ-ray branching ratios of ^{33}S levels

E_i (MeV)	Branching ratio (%) for decay to E_f (MeV) $E_f = 0$	0·84	1·97	2·31	2·87	2·93	2·97	3·22	3·83
1·97	100	<2							
2·31	33±2	67±2	<5						
2·87	100	<3	<3	<3					
2·93	41±5	<4	59±5	<4					
3·22	42±2	58±2	<1	<3	<3	<4	<3		
3·83	69±6	<13	9±3	22±5	<7	<11	<11	<3	
3·94	61±3	16±2	12±2	5±3	6±1	<6	<3	<3	
4·21	<7	93±2	<8	7±2	<3	<3	<3	<3	
4·43	53±5	21±3	19±3	7±2	<2	<2	<2	<2	<2

4·43 MeV Level

The particle groups from the 4·43 and 4·38 MeV states were poorly resolved but, as Fig. 2 shows, the latter level was also poorly excited and good data were obtained for the 4·43 MeV level. A weak branch to the 2·31 MeV level was observed in addition to decays to the ground, 0·84 and 1·97 MeV states reported by Carr *et al.* (1973). A correlation analysis of all the major decays limited the possible spins to $J = 1/2-5/2$. Our mixing ratio solutions for $J = 5/2$ would require E3 or M3 enhancements of >1400 W.u. for the 4·43→0·84 MeV transition, and the M2 enhancement of >180 W.u. required for the 4·43→1·97 MeV transition for $J^{\pi} = 1/2^{-}$ is also unacceptable, so that the spin–parity of this level must be $1/2^{+}$ or $3/2^{\pm}$.

Discussion

Our branching and mixing ratio results are generally consistent with previous data, apart from the decay modes found for the high energy states. Our use of a coincidence technique has allowed us to pick out weak branches that were previously unreported.

Firm spin–parity assignments are now known for all but two of the states around 4 MeV. A comparison between the observed states of even (or unknown) parity above 3 MeV and the even parity states predicted by the intermediate coupling model of Castel *et al.* (1971) and two shell model calculations by Wildenthal *et al.* (1971) shows that the FPSDI model of Wildenthal *et al.* appears to give a better fit than either of the other two calculations, continuing a trend apparent at lower energies, but this conclusion must remain tentative until the spins and parities of more of the levels have been fixed. Further investigation of the decay modes of these levels with high-resolution detectors may prove useful; the significance of confirming the existence of a 3·83→2·97 MeV transition has already been discussed.

Acknowledgment

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