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# Lifetimes, spins and decay modes of levels below 5·3 MeV in $^{33}S$

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**Abstract.** The reaction $^{30}Si(\alpha, n)^{33}S$ was used to populate levels in $^{33}S$ at $\alpha$ particle energies between 7·00 and 10·00 MeV. Gamma rays in $^{33}S$ were observed in a Ge(Li)–NaI(Tl) escape-suppressed and pair-escape spectrometer. The Döppler shift attenuation method was used to measure the mean lifetimes of 20 levels and to set limits on the lifetimes of 3 levels in $^{33}S$. The analysis of angular distributions of $\gamma$ rays together with the measured lifetimes and branching ratios gave $\gamma$ ray multipole mixing ratios and spin and parity assignments of $\frac{7}{2}^+$, $(\frac{5}{2}, \frac{9}{2})^+$, $(\frac{3}{2}^+, \frac{5}{2})$ and $(\frac{7}{2}, \frac{11}{2})^-$ for the levels at 2971, 4050, 4145 and 4868 keV respectively. Strutinsky-type calculations have been made for $^{33}S$ which give insight into the successes of the shell model and the intermediate coupling model in describing the properties of the low lying positive parity states. Negative parity states are discussed in terms of the vibrational model and collective rotational model. Mean lifetimes of four levels in $^{33}P$ have also been obtained, the levels being populated in the $(\alpha, p)$ reaction.

## 1. Introduction

The nucleus $^{33}S$ is in an interesting region of the s–d shell; the nuclei $^{28}Si$ and $^{29}Si$ are known to have rotational band structure corresponding to weak oblate deformations, $^{32}S$ is found to be prolate from measurements of the quadrupole moment of the first excited $2^+$ state (Nakai *et al* 1970) and $^{33}S$ itself has a ground state quadrupole moment which may indicate an oblate deformation. These changes in deformation in the sulphur isotopes suggest that these nuclei are 'soft' to shape changes which is consistent with the interpretation, suggested by lifetime data, that levels in the nuclei $^{32}S$ (Ollerhead *et al* 1970) and $^{34}S$ (Greene *et al* 1970) may be classified in terms of phonon vibrations. Detailed intermediate coupling calculations for the nuclei $^{33}S$ and $^{34}S$, which compare well with the available data, have been made by Castel *et al* (1971). Other calculations include those by Glaudemans *et al* (1971) who claim that the properties of the positive parity states of the nucleus $^{33}S$ are particularly well reproduced by their calculations which use a shell model with a modified surface delta interactions (MSDI) to represent the effective extra-core nucleon–nucleon interaction. More recently Wildenthal *et al* (1971) have extended these shell model calculations allowing some of the shell model parameters to vary while still keeping the surface delta interaction (FPSDI).

The experimental level energies in $^{33}S$ have been measured by Endt and Paris (1958) using a high resolution magnetic spectrometer. The $^{32}S(d, p)^{33}S$ reaction has

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been used by Dalton *et al* (1961) and Mermaz *et al* (1971) to determine stripping $l$ values. Pick-up $l$ values and spectroscopic factors have been measured using the $^{34}S(\tau, \alpha)^{33}S$ reaction by Dubois (1968) and Leighton and Wolff (1970). The spins of the first three and of the fifth excited states of $^{33}S$ are known from correlation work (O'Dell *et al* 1966, Becker *et al* 1966, Cummings and Donahue 1970a, b, Toulemonde and Schultz 1972) which also gives mixing ratios both for transitions from these four states and for some higher states for which unique spins have not been determined. Spins of negative parity states have been measured using the $^{32}S(n, \gamma)^{33}S$ reaction (van Middelkoop and Gruppelaar 1966, Kopecký and Warming 1969). The lifetimes of the first seven states in $^{33}S$ have been measured several times (van Middelkoop and Engelbertink 1969, Ragan *et al* 1969, Brandolini *et al* 1969, Kavanagh *et al* 1970, Cummings and Donahue 1970a, b) and three determinations of the lifetime of the fifth excited state by the recoil distance method and using gas stoppers agree well (Brandolini and Signorini 1969, Ragan *et al* 1970, Kavanagh *et al* 1970).

This paper describes the measurement of lifetimes of excited states up to 5·38 MeV in $^{33}S$ using the Döppler shift attenuation method (DSAM) and the study of angular distributions of $\gamma$ rays observed to obtain spins and mixing ratios.

## 2. Experimental method

The reaction $^{30}Si(\alpha, n)^{33}S$ ($Q = -3{\cdot}504$ MeV) was used to populate levels in $^{33}S$. The targets were of 115 μg cm$^{-2}$ $^{30}Si$ element (target A) and of 700 μg cm$^{-2}$ $^{30}SiO_2$ (target B) both on Au backings and both with an isotopic enrichment of 95 %. The $\gamma$ rays were detected in a Ge(Li)–NaI(Tl) escape-suppressed and pair-escape spectrometer (Sharpey-Schafer *et al* 1971), a typical spectrum taken at a bombarding energy of 10 MeV using target B being shown in figure 1. The detector system was calibrated for energy and efficiency using $\gamma$ rays from a $^{56}Co$ source, the energies and intensities being taken from the work of Scott and Van Patter (1969). The decay scheme of $^{33}S$, for levels above 3·5 MeV excitation (figure 2) was deduced from the threshold for observation of particular $\gamma$ rays and their accurately measured energies. Our experimental level energies are given in table 1.

The attenuated Döppler shift $F$ as a function of mean nuclear lifetime $\tau$ was calculated (Blaugrund 1966) using a program (J Naser private communication) which took account of stopping in the Au target backing. The empirical correction factors in the expression for the stopping power given by Lindhard *et al* (1963) were taken as $f_e = f_n = 1$. Centroid positions of $\gamma$ ray lines were measured at angles $\theta$ between 0° and 125° at beam energies of 7·00, 8·25, 9·25 and 10·00 MeV. Experimental attenuation factors $F$ (table 1) were obtained by linear least-squares fits to plots of centroid position against $\cos\theta$ (figure 3).

Angular distributions of $\gamma$ rays were measured at five angles between 0° and 90° to the beam direction using target B. The $\alpha$ particle bombarding energies of 7·60, 8·68, 8·30 and 9·80 MeV were chosen so that the beam energy was just above threshold for a group of levels of interest. The spins of the target nucleus $^{30}Si$ and of the incoming $\alpha$ particle are both zero and, for a state populated just above threshold, most outgoing neutrons have $l = 0$. It is therefore mainly the $m_J = \pm\frac{1}{2}$ substates of these levels of the residual nucleus $^{33}S$ that are populated. The populations of the higher magnetic substates were calculated by the statistical model program MANDY (Sheldon and Van Patter 1966). The predicted populations of the $m_J = \pm\frac{3}{2}$ substates were between 20 and 30% of those of the $m_J = \pm\frac{1}{2}$ substates at the bombarding energies used. The calculated populations of $m_J = \pm\frac{5}{2}$ and higher substates were found to be less than 1% and were neglected. In order to reduce model dependence the $m_J = \pm\frac{1}{2}$ populations were allowed to vary from 10% below the predicted value up to the full $m_J = \pm\frac{1}{2}$ population. In all cases the populations giving the best fits to the experimental angular distributions were well within this range.

Where angular distributions were available for the $\gamma$ rays from one level, branching ratios were calculated from the normalization factors $A_0$, the quantity $A_0$ being obtained by least squares fits of the angular distributions to the expression:

$$W(\theta) = \sum_{\substack{k=0 \\ k \text{ even}}}^{4} A_k Q_k P_k(\cos\theta).$$

The solid angle correction factors $Q_2$ and $Q_4$ were taken as 0·995 and 0·980 respectively. In all other cases the branching ratios were obtained from spectra taken at 55° and 125° and are given in figure 2. Measured values of the ratios $a_2 = A_2/A_0$ and $a_4 = A_4/A_0$ are given in table 2 together with level spin hypotheses and mixing ratios which give acceptable fits to the data (Cline and Lesser 1970, Rose and Brink 1967).

## 3. Experimental results

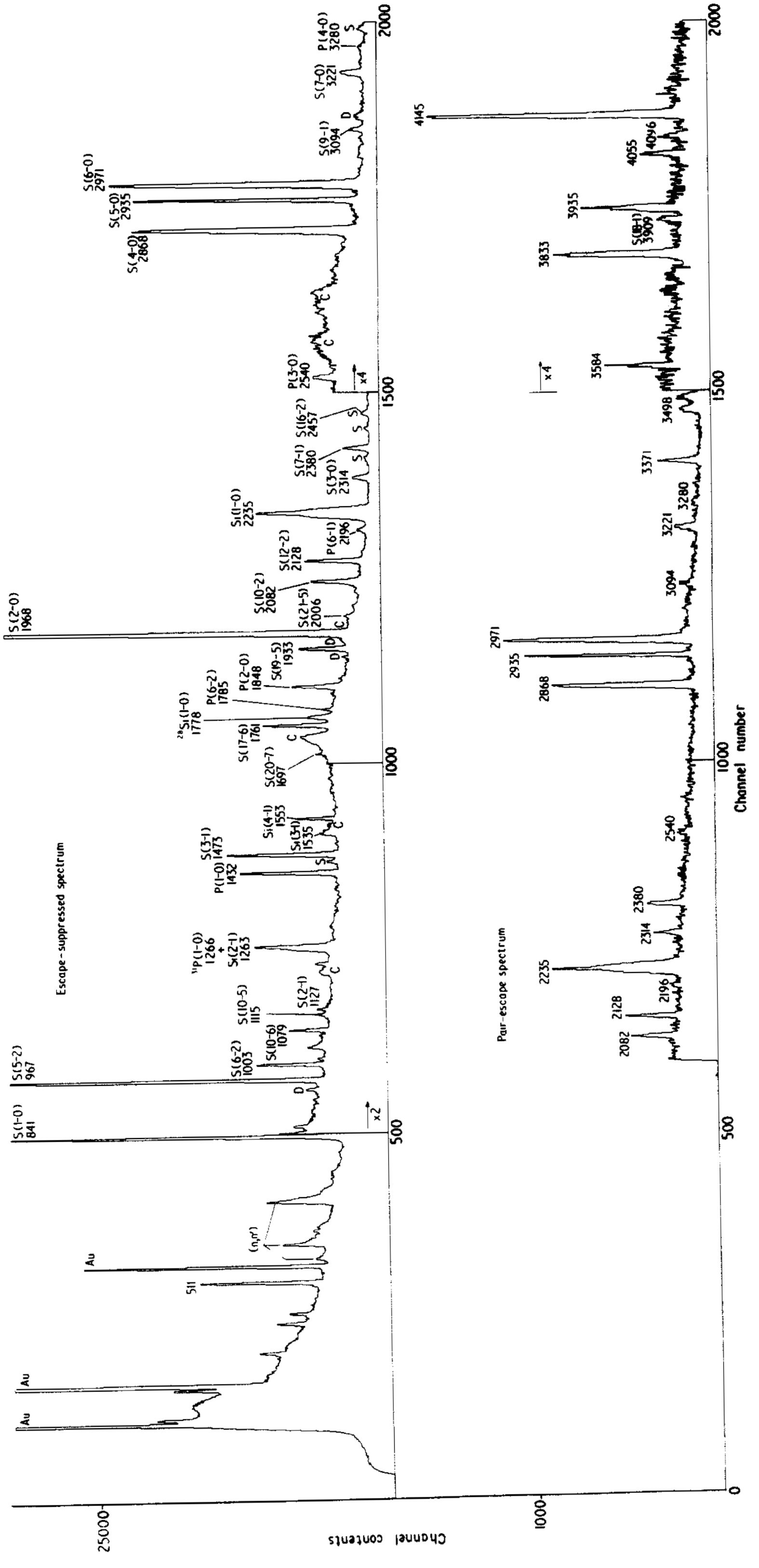
### *3.1. Mean lifetimes*

The lifetimes of 20 levels have been measured including that of a new level at 4055 keV. Limits have been set on the lifetimes of a further three levels. These results are summarized in table 1. Lifetimes measured with different targets and at different bombarding energies are generally in satisfactory agreement. In table 3 we compare our measurements with those of other workers who have previously measured the lifetimes of states up to level 7. In table 3 we have not included the 25% for uncertainties in the slowing down theory so that any systematic differences between the various results may be more easily discernable. The nuclear lifetimes given in table 3 show rather good agreement considering the wide variety of target preparations used.

### *3.2. Angular distributions*

*3.2.1. Level 4 at 2868 keV.* This level decays wholly to the ground state. Both in (d, p) stripping (Mermaz *et al* 1971) and in $(\tau, \alpha)$ pick up (Leighton and Wolff 1970) an $l = 2$ transition is seen to this level giving $J^\pi = (\frac{3}{2}, \frac{5}{2})^+$. Analysis of our data for the angular distribution of the 2868 keV $\gamma$ ray at an alpha particle energy of 7·60 MeV fails to remove this ambiguity in spin assignment.

The mirror nucleus $^{33}Cl$ has a $J^\pi = \frac{5}{2}^+$ state, which decays mainly to ground, at 2848 keV (Endt and van der Leun 1967) which is the only candidate for the mirror level of the 2868 keV level in $^{33}S$. For the level in $^{33}Cl$ the quantity $\Gamma_\gamma\Gamma_p/\Gamma = 6·3 \pm 1·3$ MeV which compares with $\Gamma_\gamma = 19 \pm 8$ MeV from our lifetime measurements for the level in $^{33}S$. The mixing ratio for the 2848 keV transition in $^{33}Cl$ is $\delta_{2848} = 0·10$ compared with $\delta_{2868} = -0·09 \pm 0·04$ for the $\frac{5}{2}^+$ solution for the transition in $^{33}S$. The similarity of the excitation energies, $\gamma$ ray width and the equal magnitude but opposite sign of the


Escape-suppressed spectrum
Pair-escape spectrum
Channel number
Channel contents

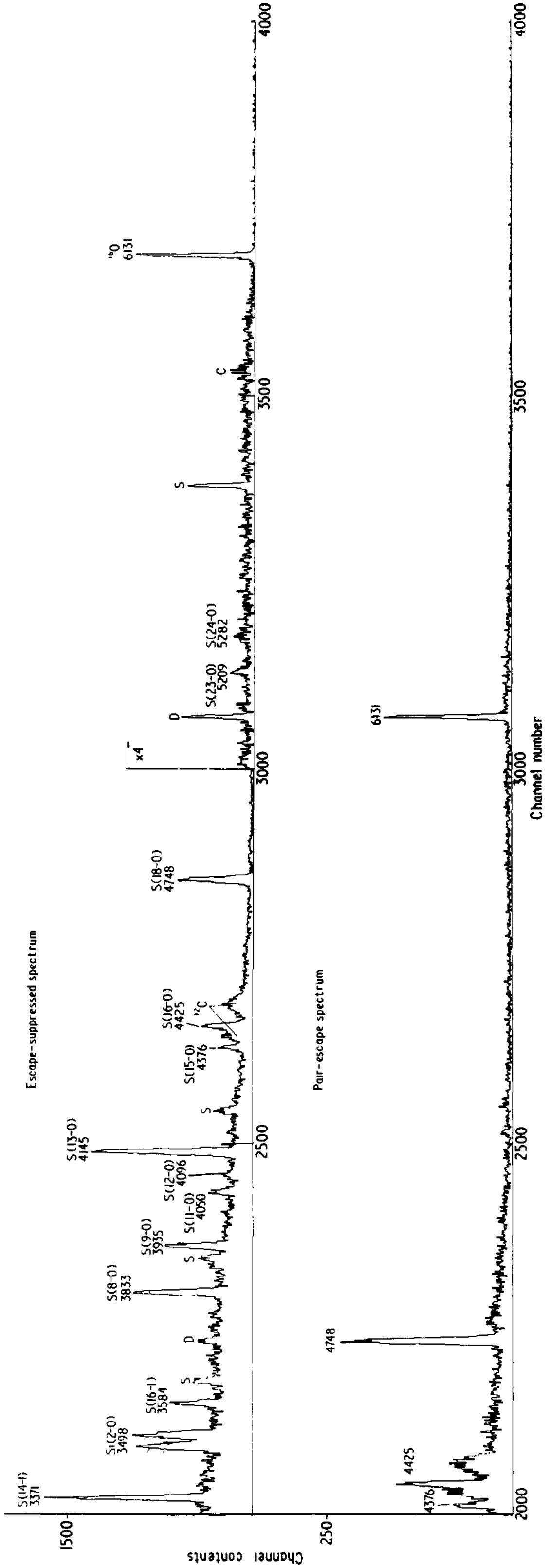



**Figure 1.** A $\gamma$ ray spectrum obtained with the escape-suppressed and pair-escape spectrometer for the bombardment of target B ($^{28}SiO_2$) with 10·00 MeV $\alpha$ particles. In the escape-suppressed spectrum peaks are labelled by their energy and by the transition from which they arise; transitions in $^{33}S$, $^{33}P$ and $^{28}Si$ being denoted by S, P and Si respectively. Compton edges, single-escape and double-escape peaks are labelled C, S and D respectively. In the pair-escape spectrum each peak is labelled with the energy of its corresponding total capture peak.

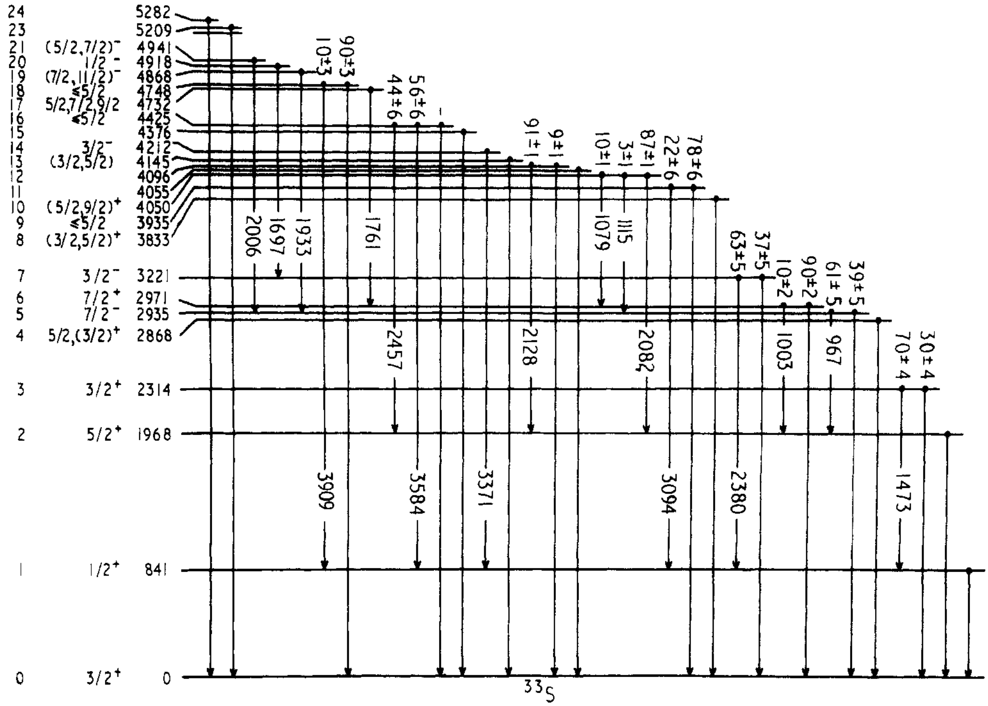



**Figure 2.** The levels of $^{33}S$ below 5·3 MeV. The level energies and branching ratios are from the present work. A partial branching ratio is given for the 4425 keV level as the ground state decay was obscured by a $^{12}C$ contamination $\gamma$ ray.

**Table 1.** Energies and lifetimes of levels in $^{33}S$ measured in the present experiment

| Level | $E_x$ (keV) | $E_\alpha$ (MeV) | Target† | $F_{average}$‡ | $\tau$§ (fs ± 25%) |
|---|---|---|---|---|---|
| 1 | 841·1 ± 0·3 | 7·00 | A | 0·123 ± 0·030 | 1700 ± 140 |
| | | 8·25 | A | 0·102 ± 0·010 | |
| 2 | 1968·0 ± 0·6 | 7·00 | A | 0·583 ± 0·036 | 189 ± 16 |
| | | 8·25 | A | 0·606 ± 0·046 | |
| 3 | 2313·7 ± 0·5 | 7·00 | A | 0·550 ± 0·027 | 198 ± 9 |
| | | 8·25 | A | 0·614 ± 0·037 | |
| | | 9·05 | A | 0·580 ± 0·023 | |
| 4 | 2868·2 ± 0·3 | 8·25 | A | 0·943 ± 0·021 | 34 ± 11 |
| | | 9·05 | A | 0·958 ± 0·018 | |
| 5 | 2935·0 ± 0·5 | 8·25 | A | < 0·034 | > 5500 |
| 6 | 2971·0 ± 0·5 | 8·25 | A | 0·786 ± 0·030 | 94 ± 5 |
| | | 9·05 | A | 0·805 ± 0·016 | |
| 7 | 3221·0 ± 0·5 | 8·25 | A | 0·893 ± 0·033 | 48 ± 13 |
| | | 9·05 | A | 0·896 ± 0·020 | |
| | | 10·00 | A | 0·932 ± 0·040 | |
| | | | B | 0·953 ± 0·011 | |
| 8 | 3833·0 ± 1·0 | 9·05 | A | 0·977 ± 0·032 | 44 ± 4 |
| | | 10·00 | A | 0·927 ± 0·015 | |
| | | | B | 0·940 ± 0·010 | |

**Table 1**—*continued*

| Level | $E_x$ (keV) | $E_\alpha$ (MeV) | Target† | $F_{average}$‡ | τ§ (fs ± 25 %) |
|---|---|---|---|---|---|
| 9 | 3935·0 ± 0·5 | 9·05 | A | 0·957 ± 0·012 | 35 ± 5 |
| | | 10·00 | A | 0·939 ± 0·026 | |
| | | | B | 0·942 ± 0·011 | |
| 10 | 4049·8 ± 0·5 | 9·05 | A | 0·431 ± 0·009 | 305 ± 7 |
| | | 10·00 | A | 0·446 ± 0·010 | |
| | | | B | 0·672 ± 0·013 | |
| 11 | 4055·0 ± 0·5 | 10·00 | B | 0·972 ± 0·014 | 18 ± 11 |
| 12 | 4096·0 ± 0·5 | 9·05 | A | 0·953 ± 0·012 | 45 ± 4 |
| | | 10·00 | B | 0·897 ± 0·010 | |
| 13 | 4145·0 ± 0·5 | 9·05 | A | 0·924 ± 0·022 | 34 ± 5 |
| | | 10·00 | A | 0·976 ± 0·012 | |
| | | | B | 0·943 ± 0·010 | |
| 14 | 4212 ± 1 | 9·05 | A | 0·929 ± 0·011 | 46 ± 4 |
| | | 10·00 | A | 0·915 ± 0·013 | |
| | | | B | 0·951 ± 0·012 | |
| 15 | 4376 ± 1 | 10·00 | B | 0·952 ± 0·014 | 34 ± 12 |
| 16 | 4425 ± 2 | 10·00 | A | 0·958 ± 0·135 | 27 ± 12 |
| | | | B | 0·961 ± 0·015 | |
| 17 | 4732 ± 1 | 10·00 | A | 0·848 ± 0·009 | 82 ± 5 |
| | | | B | 0·830 ± 0·009 | |
| 18 | 4748 ± 1 | 10·00 | A | 1·051 ± 0·010 | < 10 |
| | | | B | 1·006 ± 0·010 | |
| 19 | 4868 ± 1 | 10·00 | A | 0·393 ± 0·006 | 360 ± 8 |
| | | | B | 0·609 ± 0·015 | |
| 20 | 4918 ± 2 | 10·00 | B | 0·811 ± 0·036 | 130 ± 29 |
| 21 | 4941 ± 2 | 10·00 | B | 0·945 ± 0·016 | 39 ± 13 |
| 23 | 5209 ± 2 | 10·00 | A | 1·049 ± 0·023 | < 20 |
| | | | B | 1·018 ± 0·039 | |
| 24 | 5282 ± 2 | 10·00 | A | 0·956 ± 0·011 | 31 ± 8 |
| | | | B | 0·906 ± 0·104 | |

† Target A was 115 μg cm$^{-2}$ $^{30}Si$ on Au backing.
Target B was 700 μg cm$^{-2}$ $^{30}SiO_2$ on Au backing.

‡ $F_{average}$ is the average $F$ value of all the transitions observed using both full and double escape peaks.

§ τ is a weighted mean of the lifetimes obtained with each target at each energy. For target B τ includes an error to take account of a 10 % uncertainty in the density of the $SiO_2$. A 25 % error is shown in the time scale as an indication of uncertainty in the slowing down theory.

mixing ratios indicates that the 2848 keV level in $^{33}Cl$ and the 2868 keV level in $^{33}S$ are probably mirror levels (Glaudemans and van der Leun 1971) and hence the spin of the 2868 keV level in $^{33}S$ is probably $\frac{5}{2}^+$.

*3.2.2. Level 5 at 2935 keV.* The measured branching ratios of the decays from this level to the ground and second excited states were (39 ± 5) % and (61 ± 5) %. These errors

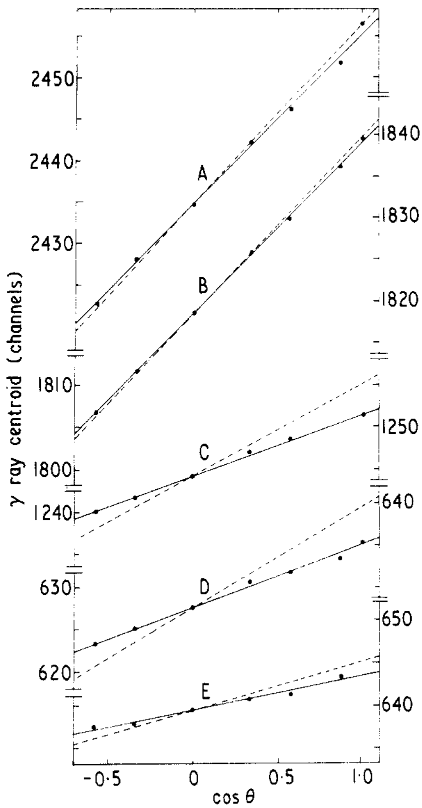



**Figure 3.** Plots of the centroids of $\gamma$ rays from the 4·05 MeV doublet in $^{33}S$ as a function of $\cos\theta$. A 4055 keV, 11–0, $F = 0{\cdot}969 \pm 0{\cdot}016$; B 4055 keV double-escape, $F = 0{\cdot}973 \pm 0{\cdot}012$; C 2082 keV, 10–2, $F = 0{\cdot}667 \pm 0{\cdot}014$; D 2082 keV double-escape, $F = 0{\cdot}683 \pm 0{\cdot}025$; E 1079 keV, 10–6, $F = 0{\cdot}708 \pm 0{\cdot}059$. The full lines are least-squares fits to the data and broken lines indicate the expected full shift.

include an allowance for the possible contamination of the 967 keV peak by the single escape peak of the 1473 keV $\gamma$ ray. The amount of contamination was estimated from the spectrum at 7·0 MeV since this energy is below threshold for the 5th excited state. The measured values disagree with those of Becker *et al* (1966) who observed a $(49 \pm 3)\%$ decay to ground.

The spin and parity of the 2935 keV level are known to be $\frac{7}{2}^-$ (Becker *et al* 1966, O'Dell *et al* 1966). Our results confirm this spin assignment uniquely. Two pairs of the mixing ratios $\delta_1(967)$ and $\delta_2(2935)$ are possible. The first pair $\delta_1 = 0{\cdot}02 \pm 0{\cdot}05$ and $\delta_2 = 4{\cdot}01 \pm 1{\cdot}25$ can be rejected as the large ratio for the ground state branch implies an E3 strength of $132 \pm 13$ Wu (using a mean lifetime of $40{\cdot}2 \pm 1{\cdot}9$ ps, table 3). The second pair of mixing ratios $\delta_1 = 0{\cdot}03 \pm 0{\cdot}07$ and $\delta_2 = 0{\cdot}18 \pm 0{\cdot}12$ are in agreement with the values of Becker *et al* (1966) and of Toulemonde and Schulz (1972) while O'Dell *et al* (1966) measured a value of $\delta_2 = 0{\cdot}48 \pm 0{\cdot}09$.

*3.2.3. Level 6 at 2971 keV.* This level decays to the ground $(90 \pm 2)\%$ and to the second excited state $(10 \pm 2)\%$ by a 1033 keV $\gamma$ ray and has a lifetime of $94 \pm 24$ fs. From a simultaneous fit to the angular distributions of both branches it was possible to reject

**Table 2.** A summary of the experimentally measured Legendre coefficients, deduced level spins and $\gamma$ ray multipole mixing ratios

| Level | $E_x$ (keV) | $E_\alpha$ (MeV) | $E_\gamma$ (keV) | $a_2$ | $a_4$ | $J_i^\pi$ | $J_f^\pi$ | $\delta$† | Transition strengths: Dipole (mWu) | Transition strengths: Quadrupole (Wu) |
|---|---|---|---|---|---|---|---|---|---|---|
| 1‡ | 841 | | 841 | | | $\frac{1}{2}^+$ | $\frac{3}{2}^+$ | \|0·18\| | 30±8 | 6·0±1·6 |
| 2‡ | 1968 | 6·30 | 1968 | −1·05±0·06 | 0·12±0·03 | $\frac{5}{2}^+$ | $\frac{3}{2}^+$ | 0·56±0·18 | 17±5 | 6±3 |
| 3‡ | 2314 | 6·70 | 2314 | −0·02±0·03 | | $\frac{3}{2}^+$ | $\frac{3}{2}^+$ | 0·28±0·08 | 3·6±1·0 | 0·2±0·1 |
| | | | | | | | | >11·4 | <0·03 | 3±1 |
| | | 6·70 | 1473 | −0·61±0·04 | | $\frac{3}{2}^+$ | $\frac{1}{2}^+$ | 0·12±0·12 | 35±10 | <3·6 |
| | | | | | | | | 1·3±0·3 | 13±5 | 42±14 |
| 4 | 2868 | 7·60 | 2868 | −0·19±0·05 | 0·02±0·05 | $\frac{3}{2}^+$ | $\frac{3}{2}^+$ | 0·47±0·13 | 33±13 | 3·6±2·2 |
| | | | | | | | | $5·7^{+8·6}_{-3·5}$ | <11 | 19±6 |
| | | | | | | $\frac{5}{2}^+$ | $\frac{3}{2}^+$ | −0·09±0·04 | 39±16 | 0·16±0·15 |
| 5 | 2935 | 7·60 | 2935 | 0·30±0·05 | −0·56±0·06 | $\frac{7}{2}^-$ | $\frac{3}{2}^+$ | 0·18±0·12 | | 0·19±0·02 |
| | | 7·60 | 967 | −0·41±0·03 | 0·01±0·03 | $\frac{7}{2}^-$ | $\frac{5}{2}^+$ | 0·03±0·07 | $(1·4±0·2)\times10^{-2}$ | <0·07 |
| 6 | 2971 | 7·60 | 2971 | 0·39±0·03 | −0·24±0·03 | $\frac{7}{2}^+$ | $\frac{3}{2}^+$ | −0·00±0·07 | | 5·4±1·4 |
| | | 7·60 | 1003 | −0·30±0·09 | 0·16±0·11 | $\frac{7}{2}^+$ | $\frac{5}{2}^+$ | 0·04±0·21 | 34±11 | <5·7 |
| 8 | 3833 | 8·68 | 3833 | 0·39±0·03 | −0·10±0·04 } | $\frac{3}{2}^+$ | $\frac{3}{2}^+$ | 0·13 > $\delta$ > −8·14 | | |
| | | 8·80 | 3833 | 0·40±0·08 | −0·09±0·09 } | $\frac{5}{2}^+$ | $\frac{3}{2}^+$ | −0·41±0·17 | 11±3 | 0·5±0·4 |
| | | | | | | $\frac{7}{2}^+$ | $\frac{3}{2}^+$ | 0·03±0·11 | 13±4 | <0·09 |
| 9 | 3935 | 8·68 | 3935 | 0·00±0·05 | 0·05±0·07 | $\frac{1}{2}^+$ | $\frac{3}{2}^+$ | | | |
| | | | | | | $\frac{3}{2}^+$ | $\frac{3}{2}^+$ | 0·23±0·17 | 11±3 | <0·4 |
| | | | | | | | | $(-0·09±0·18)^{-1}$ | <0·4 | 3±1 |
| | | | | | | $\frac{5}{2}^+$ | $\frac{3}{2}^+$ | −0·21±0·09 | 11±3 | <0·2 |
| | | | | | | | | $(0·09±0·18)^{-1}$ | <0·4 | 3±1 |
| 10 | 4050 | 8·68 | 2082 | 0·34±0·06 | −0·29±0·06 | $\frac{5}{2}^+$ | $\frac{5}{2}^+$ | $-2·2^{+0·6}_{-0·9}$ | 18±11 | 8±2 |
| | | 8·80 | 2082 | 0·36±0·07 | −0·41±0·08 | $\frac{9}{2}^+$ | $\frac{5}{2}^+$ | 0·08±0·09 | | 9·5±2·4 |
| 13 | 4145 | 8·68 | 4145 | −0·45±0·05 | −0·13±0·06 } | $\frac{3}{2}^+$ | $\frac{3}{2}^+$ | 0·55±0·19 | | |
| | | 8·80 | 4145 | −0·27±0·05 | −0·02±0·05 } | | | $4·01^{+5·5}_{-1·5}$ | | |
| | | | | | | $\frac{5}{2}$ | $\frac{3}{2}^+$ | −0·05±0·08 | | |
| 19 | 4868 | 9·80 | 1933 | 0·49±0·04 | −0·24±0·04 | $\frac{7}{2}^-$ | $\frac{7}{2}^-$ | −1·00±0·34 | 6·1±2·6 | 7±3 |
| | | | | | | $\frac{11}{2}$ | $\frac{7}{2}^-$ | 0·00±0·07 | | 13·4±3·4 |

† The sign convention of Rose and Brink (1967) is used.

‡ For completeness we give data on these levels from the work of Toulemonde and Schultz (1972) and from the compilation of Endt and van der Leun (1967).

**Table 3.** Comparison of previously measured lifetimes in $^{33}S$ with the present results.

| Level (keV) | τ (fs) Brandolini *et al* (1969) | van Middlekoop and Englebertink (1969) | Ragan *et al* (1969) | Cummings and Donahue (1970a, b) | Kavanagh *et al* (1970) | Present work† |
|---|---|---|---|---|---|---|
| 841 | $1730 \pm 200$ | $1730^{+110}_{-45}$ | $1660 \pm 340$ | $900^{+500}_{-400}$ | $3600 \pm 1800$ | $1700 \pm 140$ |
| 1968 | $125 \pm 37$ | $150 \pm 45$ | $182 \pm 22$ | $150 \pm 30$ | $90 \pm 20$ | $189 \pm 16$ |
| 2314 | $178 \pm 53$ | $140 \pm 30$ | $183 \pm 25$ | $140 \pm 40$ | $145 \pm 25$ | $198 \pm 9$ |
| 2868 | $33 \pm 13$ | $13 \pm 5$ | $< 15$ | | $< 15$ | $34 \pm 11$ |
| 2935 | $38 \pm 11$ ps | $> 7$ ps | $40{\cdot}5 \pm 2{\cdot}0$ ps | $> 1{\cdot}4$ ps | $36 \pm 8$ ps | $> 5{\cdot}5$ ps |
| 2971 | $90 \pm 31$ | $86 \pm 25$ | $82 \pm 12$ | $40^{+20}_{-10}$ | | $94 \pm 5$ |
| 3221 | | $28 \pm 9$ | $< 65$ | | | $48 \pm 13$ |

† A 25% contribution to the error for uncertainties in the slowing down theory is not included here so that any systematic differences may be more easily discernable.

all spins but $J = \frac{7}{2}$. The best fits with spins $J = \frac{1}{2}, \frac{3}{2}$ and $\frac{5}{2}$ gave $\chi^2$ of 27·7, 13·1 and 17·5 respectively. The transition strength of the ground state decay determines the parity to be positive. The best fits for $J = \frac{3}{2}$ and $\frac{7}{2}$ to the distributions of both $\gamma$ rays' angular distributions are shown in figure 4(*a*). For $J = \frac{7}{2}$ the $\chi^2$ contours are plotted in figure 4(*b*) as a function of $\tan^{-1} \delta_1$ (1003) against $\tan^{-1} \delta_2$ (2971). It can be seen that each $\gamma$ ray may have two possible values for its mixing ratio. The largest mixing ratio may be rejected in each case as it implies a large M3/E2 ratio for the major branch and an E2 strength of $126 \pm 43$ Wu for the minor branch. Thus the spin and parity of the 2971 keV level are $J^\pi = \frac{7}{2}^+$ and the mixing ratios are $\delta_1(1003) = -0{\cdot}04 \pm 0{\cdot}21$ and $\delta_2(2971) = 0{\cdot}00 \pm 0{\cdot}7$. These results are confirmed by the very recent work of Hirko and Jones (1972).

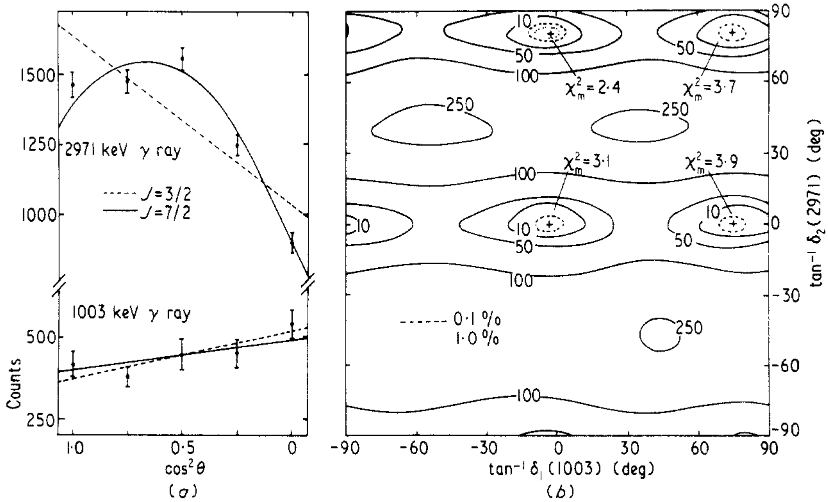



**Figure 4.** (*a*) Angular distributions of the 1003 keV and the ground state decays of the 2971 keV level in $^{33}S$. The best fits to the data with $J = \frac{3}{2}$ and $\frac{7}{2}$ are shown. (*b*) Plot of contours of $\chi^2$ for $J = \frac{7}{2}$ as a function of $\tan^{-1} \delta_1(1003)$ and $\tan^{-1} \delta_2(2971)$. Minimum values of $\chi^2$ are denoted by $\chi^2_m$ and contours of the 0·1% and 1% confidence level are shown by broken and dotted lines respectively.

*3.2.4. Level 8 at 3833 keV.* The only observed decay of the 3833 keV level is to the ground state. The measured lifetime is $44 \pm 12$ fs. There exists the possibility of a 965 keV branch from this level to the 2868 keV level which would be obscured by the 967 keV $\gamma$ ray from the level at 2935 keV to the second excited state. A simple moment calculation using the observed intensities from the 9·05 MeV run and the measured $F$ factors of the 3833, 2935 and 967 keV $\gamma$ rays allowed an upper limit of 14% to be set on the decay of the 3833 keV level to the level at 2868 keV.

The angular distributions for the 3833 keV $\gamma$ ray, measured at $\alpha$ particle energies of 8·68 and 8·80 MeV, only allowed the rejection of $J = \frac{1}{2}$ which had a minimum $\chi^2 = 39$. The mixing ratios obtained for $J = \frac{7}{2}$ were $\delta = -0.03 \pm 0.11$ and $\delta = 11.4^{+7.7}_{-5.1}$. The transition strengths rule out the large value of $\delta$ for both positive and negative parity and negative parity is excluded for the smaller value of $\delta$ as it would give an M2 strength of $117 \pm 18$ Wu to the ground state. The mixing ratios obtained for spins $\frac{3}{2}$ and $\frac{5}{2}$ were $0.13 > \delta_{3/2} > -8.14$ and $\delta_{5/2} = -0.41 \pm 0.17$ respectively. Leighton and Wolff (1970) have assigned $J^\pi = (\frac{3}{2}, \frac{5}{2})^+$ to this level as they observe a strong $l = 2$ transition to it in the $(\tau, \alpha)$ pick-up reaction.

*3.2.5. Level 9 at 3935 keV.* This level decays to ground with a $78 \pm 6$% branch and to the first excited state with a $22 \pm 6$% branch and has a lifetime of $35 \pm 10$ fs. As the full energy peak of the 3935 keV $\gamma$ ray was contaminated by the single escape peak of the 4·43 MeV $\gamma$ ray from $^{12}C$, lifetime measurements were made on the weaker branch and in the pair-escape spectrum. An angular distribution was obtained from the 8·68 MeV run by normalizing the full energy carbon peak to the uncontaminated parts of its single escape peak (after background subtraction). Using the shape of the normalized peak, the amount of contamination in the 3935 keV peak could be estimated. The resulting angular distribution is isotropic within the errors and acceptable fits could be obtained with $J = \frac{1}{2}$, $\frac{3}{2}$ and $\frac{5}{2}$. Mixing ratios (or their inverses) obtained were $\delta_{3/2} = 0.23 \pm 0.17$ or $(\delta_{3/2})^{-1} = -0.09 \pm 0.18$ and $\delta_{5/2} = -0.21 \pm 0.09$ or $(\delta_{5/2})^{-1} = 0.09 \pm 0.18$. Both of the mixing ratios expressed in inverse form imply M2 strengths of greater than 100 Wu for negative parity but they cannot be ruled out if the 3935 keV level has positive parity. Leighton and Wolff (1970) have a tentative assignment of $J^\pi = (\frac{3}{2}, \frac{5}{2})^+$ for this level based on a weak angular distribution in the $(\tau, \alpha)$ reaction which is best fitted with $l = 2$.

*3.2.6. Levels 10 and 11 at 4050 and 4055 keV.* Results of experiments using magnetic analysis for charged particles, which are summarized in the compilation of Endt and van der Leun (1967), show a level in $^{33}S$ at $4049 \pm 6$ keV. In the present experiment all $\gamma$ rays whose excitation and energy were consistent with this energy fitted a level at $4049.8 \pm 0.5$ keV except for one $\gamma$ ray whose energy was $4055.0 \pm 0.5$ keV. The Döppler shift attentuation factors $F$, measured using the $SiO_2$ target, were found to have a mean of $0.672 \pm 0.013$ for those $\gamma$ rays consistent with decay from a level at 4050 keV while the 4055 keV $\gamma$ ray was found to have $F = 0.972 \pm 0.014$. This is illustrated in figure 3 which shows the centroid against cos $\theta$ plots for the 1079 keV (10 to 6), 2082 keV (10 to 2) and 4055 keV (11 to ground) $\gamma$ rays. These results imply the existence of a doublet with levels at 4050 keV and 4055 keV. The lower level is observed to decay by 2082 keV ($87 \pm 1$%), 1115 keV ($3 \pm 1$%) and 1079 keV ($10 \pm 1$%) branches to the second, fifth and sixth excited states respectively with a measured lifetime of $304 \pm 76$ fs. The 4055 keV level decays only to the ground state with a lifetime of $18 \pm 12$ fs.

The angular distribution of the 2082 keV $\gamma$ ray at 8·68 MeV is shown in figure 5(*a*) with the best fits given by $J = \frac{5}{2}$ and $\frac{9}{2}$; $\chi^2 = 3{\cdot}1$ and $2{\cdot}0$ respectively. Minimum $\chi^2$ for spins $J = \frac{1}{2}$, $\frac{3}{2}$ and $\frac{7}{2}$ were 14·3, 15·1 and 19·0 respectively and these spin hypotheses are therefore rejected. A plot of $\chi^2$ against $\tan^{-1}\delta$ is shown in figure 5(*b*) for $J = \frac{5}{2}$ and $\frac{9}{2}$. The mixing ratios obtained were $\delta_{5/2} = -2{\cdot}2^{+0{\cdot}6}_{-0{\cdot}9}$ and $\delta_{9/2} = 0{\cdot}08 \pm 0{\cdot}09$. A possible mixing ratio of $(\delta_{9/2})^{-1} = 0{\cdot}12 \pm 0{\cdot}08$ may be rejected by the large M3 or E3 strengths it would imply. Only positive parity is possible for this state as negative parity would give M2 strengths of $261 \pm 76$ Wu for $J = \frac{5}{2}$ and $316 \pm 83$ Wu for $J = \frac{9}{2}$.

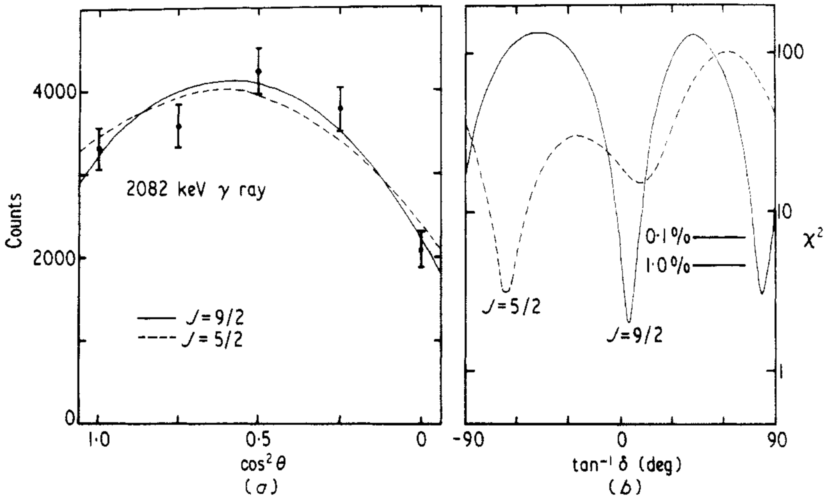



**Figure 5.** (*a*) Angular distribution of the 2082 keV decay of the 4050 keV level in $^{33}$S. The best fits to the data with $J = \frac{5}{2}$ and $\frac{9}{2}$ are shown. (*b*) Plots of $\chi^2$ against $\tan^{-1}\delta$ for the spin hypotheses $J = \frac{5}{2}$ and $\frac{9}{2}$.

These correlation results are confirmed by the very recent work of Hirko and Jones (1972).

*3.2.7. Level 13 at 4145 keV.* This level decays only to the ground state with a measured lifetime of $34 \pm 10$ fs. The angular distribution measured at 8·80 MeV gave good fits only for spins $J = \frac{3}{2}$ ($\chi^2_{\text{min}} = 0{\cdot}6$, $\delta = 0{\cdot}55 \pm 0{\cdot}19$ or $4{\cdot}01^{+5{\cdot}50}_{-1{\cdot}53}$) and $J = \frac{5}{2}$ ($\chi^2_{\text{min}} = 0{\cdot}6$, $\delta = -0{\cdot}03 \pm 0{\cdot}08$). Spin hypotheses of $J = \frac{1}{2}$ and $\frac{7}{2}$ gave minimum $\chi^2$ of 11·3 and 65·6 respectively and were therefore rejected. The second mixing ratio for $J = \frac{3}{2}$ implies a large M2/E1 ratio in the case of negative parity for the 4145 keV level and the first mixing ratio would give an M2 strength of greater than 14 Wu. This would be stronger than the largest M2 strength given in the compilation of Skorla *et al* (1966) and may be regarded as evidence for the rejection of negative parity in the case of $J = \frac{3}{2}$.

*3.2.8. Level 19 at 4868 keV.* The only decay of this level that was observed was a 1933 keV transition to the $J^\pi = \frac{7}{2}^-$ level at 2935 keV. The lifetime of the level (table 1) was measured as $360 \pm 90$ fs. Acceptable fits to the angular distribution at 9·80 MeV were only given by $J = \frac{7}{2}$ ($\chi^2_{\text{min}} = 2{\cdot}8$, $\delta = -1{\cdot}0 \pm 0{\cdot}34$) and by $J = \frac{11}{2}$ ($\chi^2_{\text{min}} = 3{\cdot}4$,

$\delta = 0{\cdot}00 \pm 0{\cdot}07$). These fits are shown in figure 6(*a*) and plots of $\chi^2$ against $\tan^{-1}\delta$ in figure 6(*b*). Minimum $\chi^2$ for $J = \frac{3}{2}$, $\frac{5}{2}$ and $\frac{9}{2}$ were 25·7, 28·3 and 39·3 respectively. An assumption of positive parity for the 4868 keV level would give rise to M2 transition strengths for the 1932 keV $\gamma$ ray of $225 \pm 95$ and $450 \pm 110$ Wu for $J = \frac{7}{2}$ and $\frac{11}{2}$ respectively. The parity of the 4868 keV level must therefore be negative.

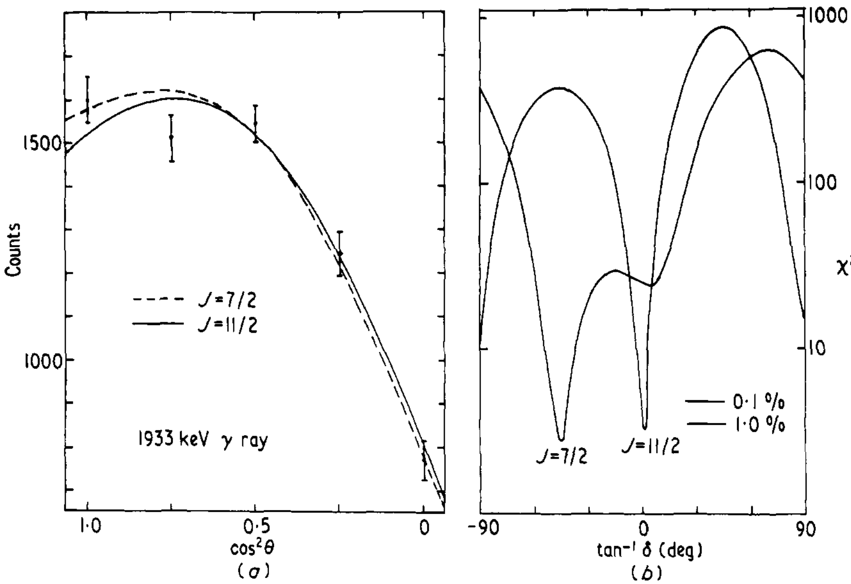



**Figure 6.** (*a*) Angular distribution of the 1933 keV decay of the 4868 keV level in $^{33}$S. The best fits to the data with $J = \frac{7}{2}$ and $\frac{11}{2}$ are shown. (*b*) Plots of $\chi^2$ against $\tan^{-1}\delta$ for the spin hypotheses $J = \frac{7}{2}$ and $\frac{11}{2}$.

### *3.3. Comments on other levels in* $^{33}S$

The level at $4732 \pm 1$ keV was observed to decay only to the 2971 keV, $J^\pi = \frac{7}{2}^+$ state with a lifetime of $82 \pm 21$ fs while the $4941 \pm 2$ keV level decays only to the 2935 keV, $J^\pi = \frac{7}{2}^-$ level with a lifetime of $39 \pm 16$ fs. In both cases pure quadrupole transitions are ruled out by the lifetimes and therefore the spins of these two levels are both limited to $J = (\frac{5}{2}, \frac{7}{2}, \frac{9}{2})$. Useful angular distributions could not be obtained for these two levels. The 1761 keV transition from the decay of the 4732 keV level is not resolved from neighbouring lines at all angles between 0° and 90° to the beam direction and the 2006 keV $\gamma$ ray from the decay of the 4941 keV level is very weak (figure 1). Recent (d, p) stripping work by Mermaz *et al* (1971) has a tentative $l = 3$ transition to the 4941 keV level which would imply $J^\pi = (\frac{5}{2}, \frac{7}{2})^-$.

The level at $4918 \pm 2$ keV was observed by van Middelkoop and Gruppelaar (1966) to decay only to the 3221 keV, $J^\pi = \frac{3}{2}^-$ level. The same decay is seen in this work and the mean lifetime is determined to be $130 \pm 44$ fs. Kopecký and Warming (1969) obtain $J^\pi = \frac{1}{2}^-$ for this level by observing the circular polarization of $\gamma$ rays after neutron capture.

No decays were observed consistent with a level reported (Endt and van der Leun 1967) at $5177 \pm 6$ keV and assigned $J^\pi = (\frac{5}{2}, \frac{7}{2})^-$.

## 4. Discussion

### *4.1. Shell model*

The most successful shell model calculations in the region of $A \simeq 33$ are those of the groups at Utrecht (Glaudemans *et al* 1971) and Oak Ridge (Wildenthal *et al* 1971). These calculations start with a spherical $^{28}$Si core and represent the residual two body interactions between particles by a modified (Glaudemans *et al* 1966) surface delta interaction (MSDI) (Green and Moszkowski 1965). The values of the two particle matrix elements and the core–particle binding energies are taken from least-squares fits to the experimental level energies for nuclei with $A = 30$ to 34. The measurements of Dubois (1968) on the $^{34}$S($\tau, \alpha$)$^{33}$S neutron pick-up reaction showed that $1d_{5/2}$ hole states are important and form a significant part of the configuration for the 2868 and 3833 keV levels in $^{33}$S. Recent MSDI calculations include up to two $1d_{5/2}$ holes in the $^{28}$Si core and show an improved agreement with experiment compared with previous calculations (Glaudemans *et al* 1964, Bouten *et al* 1967) which only considered configurations involving $2s_{1/2}$ and $1d_{3/2}$ orbitals. In order to obtain any agreement with the measured transition strengths in this region 'effective' nuclear charges and magnetic moments are used in the calculations.

The level energies predicted by the MSDI calculations are compared with the experimental values in figure 7 and the predicted E2 and M1 matrix elements are compared with experiment in table 4. The agreement of the MSDI calculations is fairly good except for the E2 strength of the third excited state to ground and the excitation energy and

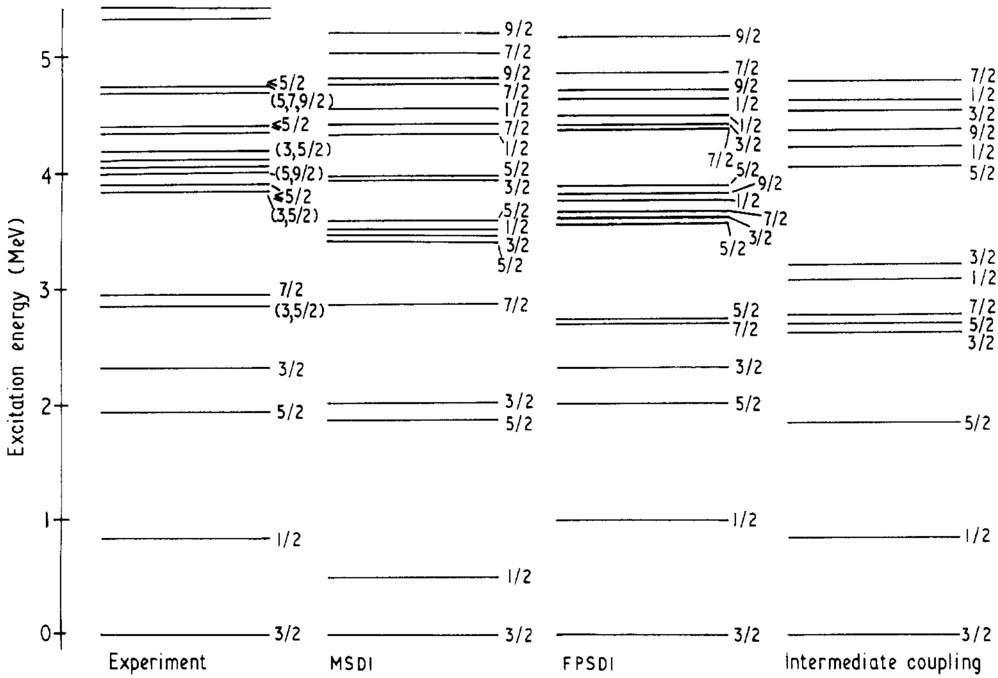



**Figure 7.** A comparison of the experimentally observed energy levels of $^{33}$S with the MSDI (Glaudemans *et al* 1971) and FPSDI (Wildenthal *et al* 1971) shell model calculations and with the intermediate coupling model (Castel *et al* 1971).

**Table 4.** Comparison of measured and predicted E2 and M1 transition strengths in $^{33}S$

| Transition | $J_i$–$J_f$ | Type of transition | $\|M\|^2$ (Wu) Experimental | Glaudemans *et al* (1971) | Wildenthal *et al* (1971) | Castel *et al* (1971) |
|---|---|---|---|---|---|---|
| 1–0 | $\frac{1}{2}$–$\frac{3}{2}$ | M1 | $(3·0\pm0·8)\times10^{-2}$ | $3·1\times10^{-2}$ | $6·3\times10^{-2}$ | $4·0\times10^{-4}$ |
| | | E2 | $6·0\pm1·6$ | 5·0 | 3·7 | 0·2 |
| 2–0 | $\frac{5}{2}$–$\frac{3}{2}$ | M1 | $(1·7\pm0·5)\times10^{-2}$† | $1·7\times10^{-2}$ | $6·8\times10^{-2}$ | $7·0\times10^{-3}$ |
| | | E2 | $5·6\pm2·9$† | 8·7 | 5·9 | 12·4 |
| 3–0 | $\frac{3}{2}$–$\frac{3}{2}$ | M1 | $(3·6\pm1·0)\times10^{-3}$‡ | $2·0\times10^{-3}$ | $8·0\times10^{-3}$ | $4\times10^{-5}$ |
| | | E2 | $0·24\pm0·12$‡ | 2·6 | 2·5 | 5·1 |
| 3–1 | $\frac{3}{2}$–$\frac{1}{2}$ | M1 | $(3·5\pm1·0)\times10^{-2}$§ | $4·3\times10^{-2}$ | $4·9\times10^{-2}$ | $4·9\times10^{-3}$ |
| | | E2 | $<3·6$ § | 6·5 | 6·0 | 1·1 |
| 4–0 | $(\frac{5}{2})$–$\frac{3}{2}$ | M1 | $(3·9\pm1·6)\times10^{-2}$ | 0·2 | $7·0\times10^{-2}$ | $4·5\times10^{-2}$ |
| | | E2 | $0·16\pm0·15$ | 2·2 | 2·1 | 0·15 |
| 6–0 | $\frac{7}{2}$–$\frac{3}{2}$ | E2 | $5·4\pm1·4$ | 4·8 | 4·3 | 6·1 |
| 6–2 | $\frac{7}{2}$–$\frac{5}{2}$ | M1 | $(3·4\pm1·1)\times10^{-2}$ | $8·0\times10^{-3}$ | | $1·4\times10^{-3}$ |
| | | E2 | $<5·7$ | 0·3 | | 12·8 |

† Calculated using $\delta = 0·56\pm0·18$ (Toulemonde and Schultz 1972).
‡ Calculated using $\delta = 0·28\pm0·08$ (Toulemonde and Schultz 1972).
§ Calculated using $\delta = 0·12\pm0·12$ (Toulemonde and Schultz 1972). Their other value $\delta = 1·3\pm0·3$ yields $|M(\mathrm{M1})|^2 = (1·3\pm0·5)\times10^{-2}$ Wu and $|M(\mathrm{E2})|^2 = 42\pm14$ Wu.

transition strengths of the predicted second $\frac{5}{2}^+$ state to ground, which may presumably be identified with the $J^\pi = \frac{5}{2}^+$ $(\frac{3}{2}^+)$ level at 2868 keV.

More recently Wildenthal *et al* (1971) have obtained better agreement with the experimental level energies by performing MSDI-type calculations but treating the two-body matrix elements, which do not involve $1d_{5/2}$ holes, as free parameters in a least squares fit to the experimental data (FPSDI). The intention of this approach is to renormalize empirically the interaction to compensate for the omission of configurations not included in the active model space. It can be seen from figure 7 that this approach considerably improves the agreement with the experimental level energies while modifying, but not improving, the overall agreement with the transition matrix elements (table 4). In particular the excitation energy and the M1 transition strength of the FPSDI predicted second $J^\pi = \frac{5}{2}^+$ level are in much improved agreement with the experimental data for the 2868 keV level. Also the lowest $\frac{9}{2}^+$ level predicted by the FPSDI calculations is nearer the experimental candidate for the lowest $\frac{9}{2}^+$ at 4050 keV. Unfortunately neither the published MSDI nor FPSDI calculations give electromagnetic matrix elements for any $\frac{9}{2}^+$ levels. The FPSDI calculations predict (figure 7) a number of positive parity levels in the region of 4·0 to 5·5 MeV excitation energy, including some with $J^\pi = \frac{7}{2}^+$ and $\frac{9}{2}^+$. Clearly more experimental data is required in this region to test and improve further the shell model calculations.

There are, at the moment, no shell model calculations for negative parity states other than those of Erné (1966), which involve only the level at 2935 keV.

### 4.2. *Intermediate coupling model*

Castel *et al* (1971) have used an intermediate coupling vibrational model to predict, with some success, the properties of levels in $^{33}S$ and $^{34}S$. In this model quasiparticles and holes are coupled via a quadrupole interaction to a $^{32}$S core in which anharmonic contributions are calculated from the splitting of the $^{32}$S two-phonon states. Parameters used in the calculations were taken from proton pick-up reactions on $^{32}$S and from the quadrupole moment and width of the $^{32}$S one-phonon state. Effective charges and $g$ factors are used for the quasiparticles. The strength of the particle–core coupling interaction was varied to give the best fit to the spacing of the energy levels in $^{33}$S and these results are shown in figure 7. The calculated E2 and M1 matrix elements are compared with experiment and the shell model calculations in table 4. The overall agreement with experiment for the vibrational model is not quite as good as that obtained with the shell model calculations, in particular the M1 transition strengths are too weak although the E2 strengths are in fair agreement with experiment. The particularly poor agreement with the experimental data for the first excited state has been noted by Castel *et al* (1971) who point out that the properties of this particular state are very sensitive to the precise definition of the quasiparticles used.

The calculations of Castel *et al* (1971) do not include any consideration of negative parity states. The lowest two negative parity levels are at 2935 keV and 3221 keV and they contain a major part of the $1f_{7/2}$ and $2p_{3/2}$ single particle widths respectively (Dalton *et al* 1960, Mermaz *et al* 1971). Weak coupling of $1f_{7/2}$ and $2p_{3/2}$ particles or quasiparticles to a one-phonon vibration of the $^{32}$S core will produce a quintet of negative parity states ($J = \frac{3}{2}$ to $\frac{11}{2}$) with their centre of gravity at about 5165 ($=2935+2230$) keV and a quartet of negative parity states ($J = \frac{1}{2}$ to $\frac{7}{2}$) with a gravicentre of 5451 keV. All these levels should decay to their parent single particle state with enhanced E2 strengths equal to the one-phonon transition strength in $^{32}$S of $7{\cdot}0 \pm 0{\cdot}7$ Wu (Ingebretsen *et al* 1971). Possible candidates for members of the quintet are the 4868 keV level with $J^\pi = (\frac{7}{2}, \frac{11}{2})^-$, whose only observed decay is to the present $\frac{7}{2}^-$ level at 2935 keV with a 6 Wu ($J = \frac{7}{2}$) or a 13 Wu ($J = \frac{11}{2}$) transition strength, and the 4941 keV $J^\pi = (\frac{5}{2}, \frac{7}{2})^-$ level whose only observed decay is also to the 2935 keV level. The mixing ratio $\delta$ is unknown for the latter transition and the E2 strength would be given by $103(1+\delta^{-2})^{-1}$ Wu. Other known negative parity levels in this region are at 4213 keV ($J^\pi = \frac{3}{2}^-$) and 4918 keV ($J^\pi = \frac{1}{2}^-$). In the mirror nucleus $^{33}$Cl several negative parity states just above 5 MeV in excitation have recently been observed by Kozub and Youngblood (1972) using the $^{32}$S($\tau$, d)$^{33}$Cl reaction.

### 4.3. *Rotational collective models*

We have investigated the theoretical possibility of rotational bands existing in $^{33}$S by making calculations of the type first performed for heavy nuclei by Strutinsky (1967). The total nuclear energy is calculated as a function of the single particle neutron orbital and the deformation of the $^{32}$S core. The calculation is very similar to that performed for $^{29}$Si by Ragnarsson and Nilsson (1970) who give a description of the details. The deformation energy of the core is taken to be that of a liquid drop and the single particle energy is given by the usual Nilsson formula. The results for $^{33}$S are shown in figure 8. The lowest orbitals are those for a $1d_{3/2}$ particle with $\Omega = \frac{3}{2}$ (oblate deformation) and $\Omega = \frac{1}{2}$ (prolate deformation). Close in energy to these is a band based on a $2s_{1/2}$ hole which may have either a prolate or an oblate deformation. In short, figure 8 shows that the nucleus $^{33}$S is 'soft' to deformations for its low lying positive parity states which gives a qualitative explanation for the success of the shell model and intermediate coupling vibrational calculations. For negative bands, based on a $1f_{7/2}$ orbital there are sharp minima in the energy surface and low lying $K = \frac{7}{2}^-$ (oblate) and $K = \frac{1}{2}^-$

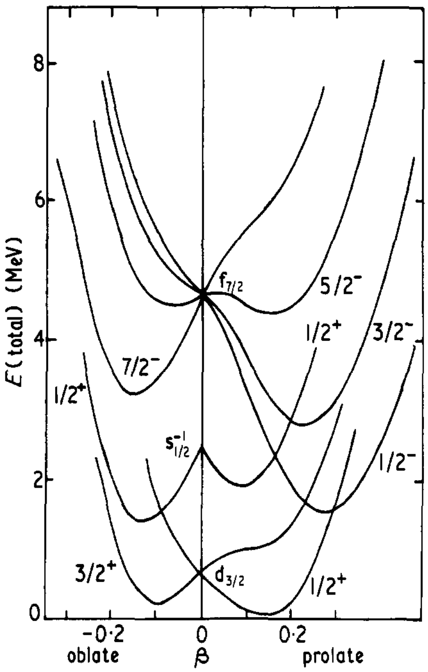



**Figure 8.** The total energy for $^{33}S$ as a function of distortion for the odd neutron associated with orbits of given $\Omega$ and $\pi$ calculated after the method of Strutinsky (1967). Only $1d_{3/2}$ and $1f_{7/2}$ particle orbits and $2s_{1/2}$ hole orbits have been considered and no pairing forces have been included. We have taken the collective parameters as $\mu_n = \mu_p = 0{\cdot}308$ and $\kappa_n = \kappa_p = 0{\cdot}210$.

(prolate) bands are predicted. In our calculation the prolate $K^\pi = \frac{1}{2}^-$ band should lie lowest, in which case the lowest experimentally observed negative parity states at 2935 and 3221 keV would have to be taken to be the $J^\pi = \frac{7}{2}^-$ and $\frac{3}{2}^-$ members of a $K^\pi = \frac{1}{2}^-$ band with the band head at the lowest identified $\frac{1}{2}^-$ state at 4918 keV, and the $\frac{11}{2}^-$ member would be at 4868 keV. In spite of these assignments giving a strong E2 in-band transition of 13 Wu from the $\frac{11}{2}^-$ to $\frac{7}{2}^-$ levels, the level ordering would require a decoupling parameter $a < -6$ compared with $a > -4$ required by the model. An alternative scheme would have the $\frac{7}{2}^-$ level at 2935 keV as the band head of an oblate $K = \frac{7}{2}^-$ band and the $\frac{3}{2}^-$ level at 3221 keV the lowest member of a $K = \frac{1}{2}^-$ band together with a $\frac{1}{2}^-$ level at 4918 keV and a $\frac{7}{2}^-$ member at 4868 keV or 4941 keV which would now give a more reasonable decoupling parameter of $a \simeq -3$.

Early attempts by Bishop (1959) and Bhatt (1962) to give a collective description of the positive parity states in terms of deformed bands were hampered by lack of experimental information. If the spin of the 4050 keV level is $\frac{9}{2}^+$ then the four levels at 0 ($\frac{3}{2}^+$), 1968 ($\frac{5}{2}^+$), 2971 ($\frac{7}{2}^+$) and 4050 keV ($\frac{9}{2}^+$) show qualitative rotational behaviour with fairly enhanced E2 transition strengths among themselves. A plot of excitation energy against $J\,(J+1)$ shows that the $\frac{5}{2}$, $\frac{7}{2}$ and $\frac{9}{2}$ proposed members are in an approximately straight line with a gradient giving $\hbar^2/2\mathscr{I} = 140$ keV, while the $\frac{3}{2}^+$ band head is depressed. A similar situation has been observed in $^{29}Si$ (Bailey *et al* 1972) where an oblate $K^\pi = \frac{3}{2}^+$ band has a band head depressed from a gradient given by $\hbar^2/2\mathscr{I} = 160$ keV. In such a model the 841 keV level would be viewed as a $2s_{1/2}$ hole, in keeping with its spectroscopic factor measured in pick-up reactions, and would be the band head of a $K^\pi = \frac{1}{2}^+$ band with higher members at 2314 ($\frac{3}{2}^+$) and 2868 keV ($\frac{5}{2}^+$), again in analogy with $^{29}$Si. However, the ground state quadrupole moment and the measured E2 transition strengths between positive parity levels are not large enough to give convincing evidence of rotational behaviour and in particular the 1968 keV transition to ground which would have to be a $K^\pi = \frac{3}{2}^+$ in-band transition has a mixing ratio of +0·56, whereas if both levels were members of an oblate $K^\pi = \frac{3}{2}^+$ rotational band the mixing ratio should be negative (Main *et al* 1970). It would seem then that there would have to be at best a great deal of band mixing in order to reproduce the experimental data on the positive parity states and that there is insufficient data at the moment on negative parity states to determine whether these might have rotational band structure or not.

## 5. Lifetimes in $^{33}$P

In this experiment levels in $^{33}$P were observed by the $^{30}$Si(α, p)$^{33}$P reaction. These levels were very weakly excited compared with the levels in $^{33}$S (figure 1). Nevertheless, with the exception of the 4th excited state of $^{33}$P, level energies and lifetimes could be measured up to the 6th excited state. These measurements are summarized in table 5.

**Table 5.** Level energies, *F* factors and lifetimes in $^{33}$P

| $E_x$ (keV) | Transition | $E_\alpha$ | Target† | *F*‡ | τ§ (fs ± 25%) |
|---|---|---|---|---|---|
| 1431·8 ± 0·2 | 1–0 | 7·00 | A | 0·297 ± 0·005 | 525 ± 20 |
| 1847·9 ± 0·2 | 2–0 | 8·25 | A | 0·145 ± 0·006 | 1200 ± 10 |
| | 2–0 | 9·05 | A | 0·152 ± 0·040 | |
| 2539·7 ± 0·5 | 3–0 | 10·00 | A | 1·018 ± 0·005 | < 10 |
| | 3–0D | | | 1·024 ± 0·080 | |
| 3489 ± 2 | 5–2 | 10·00 | B | 0·938 ± 0·043 | 43 ± 31 |
| 3628 ± 1 | 6–1 | 10·00 | B | 0·714 ± 0·044 | 160 ± 39 |

† Target A was 115 μg cm$^{-2}$ $^{30}$Si element on Au backing; Target B was 700 μg cm$^{-2}$ $^{30}SiO_2$ on Au backing.
‡ $F_{average}$ is the average *F* value of all the transitions observed using both full and double escape peaks. $F_{average}$ includes a 1% error for uncertainty in the effective beam energy.
§ For target B τ includes an error to take account of a 10% uncertainty in the density of the $SiO_2$. Otherwise errors due to the uncertainty in the slowing down theory are not included but are shown as a 25% error in the time scale.

Previous lifetime measurements have been reported for only the first two levels by Currie *et al* (1969) who obtain 790 ± 220 and 1360 ± 170 fs for the first and second excited states, which compare with our measurements of 525 ± 130 and 1200 ± 300 fs.

It is not appropriate to discuss the level structure of $^{33}$P in detail here, but it may be mentioned that the existing experimental data, including our value for the lifetime of the $J^\pi = \frac{7}{2}^+$ for the 3628 keV level, give reasonable agreement with the shell model calculations of Glaudemans *et al* (1971); also, it may be noted that the level structure including spin sequences, energies, mixing ratios and lifetimes, are very similar to those of $^{29}$Si which would lead to interpreting the ground, 1848, 2540 and 3628 keV levels as the $J = \frac{1}{2}, \frac{5}{2}, \frac{3}{2}$ and $\frac{7}{2}$ members of a $K = \frac{1}{2}^+$ band based on Nilsson orbit 9 while the 1432 and 3489 levels would be $J = \frac{3}{2}$ and $\frac{5}{2}$ members of a $K = \frac{3}{2}^+$ band based on orbit 9.

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*Note added in proof.* In a recent measurement (Butler P A *et al* 1973 *J. Phys.* A: *Math., Nucl. Gen.* **6** L15–8) of $\gamma$ ray linear polarizations we have shown that the levels at 2868, 4050, 4096 and 4868 keV have $J^\pi = \frac{5}{2}^+, \frac{9}{2}^+, \frac{7}{2}^+$ and $\frac{11}{2}^-$ respectively. (NB in table 1 of Butler *et al* (1973), the signs of three quantities are incorrect. The correct values are: $\delta = -0{\cdot}14 \pm 0{\cdot}02$ for the 2868 keV level with $J^\pi = \frac{5}{2}^+$; $\delta = -1{\cdot}28 \pm 0{\cdot}09$ for the 4868 keV level with $J^\pi = \frac{7}{2}^-$; and $P_T = -0{\cdot}34 \pm 0{\cdot}03$ for the 4050 keV level with $J^\pi = \frac{5}{2}^+$.)

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