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Accurate Branching Ratio Measurements in $^{31}P(p, \gamma)^{32}S$

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Abstract

The reaction $^{31}P(p, \gamma)^{32}S$ has been investigated in the proton energy range 0·4–1·75 MeV. Gamma ray spectra were measured for 25 resonances with Ge(Li) detectors which were carefully calibrated for relative peak efficiencies. Allowance was made for the effect of anisotropies in all the emitted γ-rays. The spectra have been analysed to give branching ratios for bound and unbound levels. Comparisons made with previous work reveal some differences.

Introduction

An example of the use of Ge(Li) detectors in the accurate measurement of γ-ray branching ratios has been outlined in the preceding paper (Boydell and Sargood 1975; referred to hereafter as Paper I). The accuracy and reliability of such results is dependent on the detector calibrations, experimental arrangements and techniques of spectrum analysis, as discussed in Paper I. The present paper describes the measurement of branching ratios of levels in ^{32}S up to 10·6 MeV, excited via the reaction $^{31}P(p, \gamma)^{32}S$, using the calibrations and techniques of Paper I.

Experimental Details

The measurements were carried out with the 800 kV electrostatic accelerator at the University of Melbourne, and with the 3 MV Van de Graaff accelerator at the AAEC Research Establishment at Lucas Heights, N.S.W. Targets of Zn_2P_3 and elemental phosphorus were prepared by evaporation onto 0·025 cm gold backings. The elemental phosphorus targets were deposited as the (stable) red allotrope, using a technique similar to that of Hooton (1964). The elemental targets were used for most measurements; only where very thin targets were required were the Zn_2P_3 ones used, as very thin elemental targets were difficult to prepare. Target thicknesses were chosen to be larger than the natural resonance widths, but much smaller than the resonance separation. Other experimental details are covered in Paper I.

Branching Ratio Results

Resonance levels

The measured branching ratios of resonance levels in $^{31}P(p, \gamma)^{32}S$ for $E_p < 1750$ keV are presented in Table 1. The errors (displayed as superscripts) arise from peak area errors and the estimated uncertainties in the efficiency calibrations. The values in parentheses are those for which secondary components were obscured, and are tentative. The upper limits quoted for unobserved transitions were determined as

Table 1. Branching ratios of resonance levels in $^{31}P(p,\gamma)^{32}S$

The branching ratios shown for each resonance are normalized so that the sum of all non-tentative primary transitions (printed in bold) equals 100%. The errors which arise from uncertainties in the peak areas and in the efficiency calibrations are displayed as superscripts

Final level E_x (MeV)	J^π	439 1^+	541 2^-	642 1^-	811 2^+	821 1	874 2^+	888 $2^-,3,4^-$	895 $1^-,2^+$	984 $2^+,3^-$	1016 1^-	1057 1,2	1090 1,2,3,4
		Proton energy (keV) and J^π of resonance											
0	0^+	**40**^{5}	**2·3**$^{0·2}$	**85**^{7}	**0·4**$^{0·2}$	**81**^{8}	**6·6**$^{0·7}$	<0·4	**4·0**$^{0·5}$	**0·7**$^{0·2}$	**10**^{1}	**1·7**$^{0·2}$	<1·1
2·23	2^+	**19**^{2}	**62**^{5}	<2·3	**58**^{5}	**10**^{1}	**43**^{7}	**0·8**$^{0·2}$	**19**^{2}	**20**^{2}	**51**^{4}	**10**^{1}	**41**^{4}
3·78	0^+	<0·8	<0·5	<1·8	<0·4	**1·8**$^{0·3}$	**6·4**^{2}	<1·2	<0·8	<0·8	<0·5	<0·6	<1·3
4·28	2^+	<1·1	**1·9**$^{0·5}$	**8**^{1}	<0·4	<0·2	**2·8**$^{0·8}$	<0·9	**22**^{2}	**10**^{2}	**1·8**$^{0·6}$	**3·8**$^{0·5}$	**1·2**$^{0·7}$
4·46	4^+	<0·7	<0·6	<0·8	<1·2	<0·4	(1·2)$^{0·5}$	<0·7	<0·5	**1·7**$^{0·4}$	<1·3	(0·2)$^{0·1}$	<1·4
4·70	1^+	**13**^{1}	**1·6**$^{0·6}$	<3	**40**^{3}	**2·3**^{1}	**26**^{2}	<0·9	**5·2**$^{0·9}$	<0·9	**2·4**$^{0·5}$	**5·0**^{1}	<11
5·01	3^-	<1·1	**10**^{1}	**3·1**$^{0·7}$	<0·6	<0·3	**2·1**^{1}	**39**^{3}	**3·0**$^{1·5}$	**50**^{3}	<1	<7	<1·1
5·41	3^+	<0·9	<0·9	<1·4	**1·7**$^{0·4}$	<0·2	<1·3	<0·9	<1·4	<1·5	<1·7	<1·2	**2·7**^{1}
5·55	2^+	<1·4	(1·2)$^{0·3}$	<2	<0·5	**2·2**$^{0·3}$	<1·8	<0·8	**1**$^{0·5}$	<0·7	<0·9	**11**^{1}	**35**^{3}
5·80	1^-	<0·9	**1·1**$^{0·3}$	**3·6**$^{0·8}$	<0·8	<0·7	**3·6**$^{0·9}$	<0·4	**20**^{2}	**2·7**$^{0·3}$	**5·7**^{1}	<0·3	<1·3
6·22	2^-	**1·8**$^{0·3}$	**18**^{3}	<2·4	<0·6	<0·3	<1·7	**13**$^{1·4}$	**20**^{2}	**5·6**$^{0·7}$	<2·2	<0·5	<2·3
6·62	4^-	<0·4	**1·3**$^{0·3}$					**41**^{3}	<0·3	<0·6	<0·5		<1·1
6·67	$1,2^{+A}$	<0·4	<0·4								**1·4**$^{0·4}$	(3·6)$^{0·4}$	<5
6·76	$2^-,3$		<0·4					**5·1**^{2}					
6·85													**7·4**^{1}
7·00	1^+						**3·1**$^{0·5}$					**24**^{3}	
7·12	2^+	**19**^{4}		<8·3			**3·1**$^{0·5}$	<0·5		**8·6**$^{0·6}$	**27**^{2}	**45**^{6}	**9**^{1}
7·19	1^+					**2·1**$^{0·9}$							
7·48	$1^-,2,3$					(0·3)$^{0·1}$							**2·9**$^{0·3}$
7·54	0^+	**7·4**$^{0·9}$						<0·4					(0·8)$^{0·4}$
7·70	$2,3,4^+$							**1·0**$^{0·5}$	<0·6				
7·95								<0·7	**1·2**$^{0·3}$				
8·13	1^+		**1·9**$^{0·3}$				**2·9**$^{0·7}$		**4·2**$^{0·6}$				

Table 1 (*Continued*)

Final level E_x (MeV)	J^π	Proton energy (keV) and J^π of resonance: 1121 1^-	1151 3^-	1155 2^+	1251 2^-	1400 2^+	1403 3^-	1411 2^+	1438 4^-	1473 2^+	1515 1^-	1557 2^+	1583 $4^{(-)}$	1699 $1^\pm,2^\pm,3^-$
0	0^+	76^{7}	<0·5	$0\cdot7^{0\cdot1}$	$2\cdot0^{0\cdot2}$	$1\cdot6^{0\cdot2}$	$0\cdot3^{0\cdot2}$	$7\cdot6^{0\cdot8}$	<0·3	$4\cdot0^{0\cdot4}$	15^{2}	$1^{0\cdot2}$	<0·9	$8\cdot8^{0\cdot9}$
2·23	2^+	$8\cdot1^{0\cdot9}$	31^{3}	62^{6}	32^{3}	12^{1}	14^{1}	$9\cdot0^{0\cdot9}$	$0\cdot9^{0\cdot1}$	35^{4}	68^{6}	12^{1}	$0\cdot8^{0\cdot3}$	21^{2}
3·78	0^+	$2\cdot8^{0\cdot6}$	<0·9	<0·6	<0·4	<0·7	<0·2	$2\cdot8^{0\cdot6}$	<0·1	<1·5	<2·3	$0\cdot6^{0\cdot2}$	<0·3	<2·5
4·28	2^+	$2\cdot2^{0\cdot3}$	<1	$1\cdot6^{0\cdot5}$	$1\cdot5^{0\cdot2}$	$6\cdot8^{0\cdot6}$	<1	11^{1}	<0·2	$2\cdot8^{0\cdot4}$	<0·8	40^{3}	$1\cdot8^{0\cdot5}$	11^{1}
4·46	4^+	<1	$7\cdot6^{0\cdot7}$	<0·9	<0·5	$5\cdot3^{0\cdot5}$	21^{2}	<1	$9\cdot7^{0\cdot7}$	<3	<1·3	<0·3	$1\cdot4^{0\cdot4}$	<1·4
4·70	1^+	$1\cdot5^{0\cdot3}$	<0·4	21^{2}	$0\cdot9^{0\cdot2}$	19^{2}	<1	$4\cdot3^{0\cdot6}$	<0·1	<1	12^{1}	$9\cdot2^{0\cdot7}$	<0·3	$2\cdot5^{0\cdot8}$
5·01	3^-	<0·3	$6\cdot5^{0\cdot6}$	$0\cdot9^{0\cdot2}$	13^{1}	$4\cdot9^{0\cdot7}$	62^{5}	<1·4	$4\cdot7^{0\cdot5}$	24^{1}	<1·3	$2\cdot3^{0\cdot2}$	$6\cdot4^{0\cdot5}$	$3\cdot3^{0\cdot6}$
5·41	3^+	<0·3	$6\cdot6^{0\cdot6}$	<1	$3\cdot8^{0\cdot7}$	$2\cdot9^{0\cdot3}$	$0\cdot4^{0\cdot2}$	$3\cdot2^{0\cdot3}$	<0·2	$2\cdot2^{0\cdot8}$ B	<2·6	12^{1}	<0·2	$7\cdot4^{0\cdot6}$
5·55	2^+	<0·8	28^{2}	$9\cdot4^{0\cdot9}$	<0·7	$6\cdot8^{0\cdot7}$	<1	$2\cdot5^{0\cdot5}$	<0·3	<1·7	<11	$2\cdot7^{0\cdot3}$	<0·5	$2\cdot7^{0\cdot5}$
5·80	1^-	<0·3	$(1\cdot1)^{0\cdot3}$	<0·9	<1·5	<0·6	<0·8	<1	—	$(2\cdot4)^{0\cdot8}$	<3·4	<0·6	<1	<2·1
6·22	2^-	<0·4	$2\cdot4^{1\cdot0}$	<1·1	46^{3}	<0·7	<0·6	$4\cdot2^{0\cdot9}$	—	29^{2}	<2·5	$2\cdot0^{0\cdot3}$	<2	<7·3
6·62	4^-	<0·5	$3\cdot5^{0\cdot3}$	$1\cdot2^{0\cdot4}$	<0·7	<0·6	<0·6	<0·9	76^{5}	<1·4	<2·6	<0·6	82^{5}	<1·5
6·67	$1,2^+$ A	—	<0·6	—	<0·7	$(0\cdot7)^{0\cdot2}$	$0\cdot7^{0\cdot2}$	<1	—	$(1\cdot8)^{0\cdot9}$	<2·2	14^{1}	—	<3
6·76	$2^-,3$							<1·1	$2\cdot6^{0\cdot6}$		<2·9		$2\cdot2^{1\cdot7}$	<1·5
6·85			$6\cdot5^{0\cdot7}$	$0\cdot8^{0\cdot2}$				<1				<0·6		<1·5
7·00	1^+	$0\cdot4^{0\cdot1}$		$1\cdot8^{0\cdot5}$				47^{3}			<2·1	<0·6		<4
7·12	2^+	$1\cdot5^{0\cdot2}$	$4\cdot0^{0\cdot7}$	$0\cdot8^{0\cdot3}$		41^{3}	$2\cdot0^{1\cdot5}$	$3\cdot2^{1\cdot0}$						40^{4}
7·19	1^+					$(0\cdot5)^{0\cdot1}$		$(0\cdot9)^{0\cdot2}$				$1\cdot2^{0\cdot9}$		$3\cdot8^{0\cdot4}$
7·48	$1^-,2,3$		$3\cdot9^{0\cdot3}$			$(1\cdot1)^{0\cdot2}$	<0·4			<2·3		$2\cdot6^{0\cdot9}$		
7·54	0^+							$5\cdot4^{0\cdot7}$						
7·70	$2,3,4^+$				$(0\cdot3)^{0\cdot1}$				<0·3				<0·3	
7·95									$5\cdot6^{0\cdot6}$				$3\cdot9^{0\cdot4}$	
8·13	1^+	$7\cdot8^{0\cdot6}$								$3\cdot4^{1\cdot0}$	5^{1}		$0\cdot8^{0\cdot5}$	

[A] J^π values from Moss *et al.* (1973).

[B] It was not possible to distinguish the $R\rightarrow5\cdot41$ MeV transition from the $7\cdot12\rightarrow2\cdot23$ MeV transition, and similarly for the $5\cdot41\rightarrow2\cdot23$ and $R\rightarrow7\cdot12$ MeV transitions. The value of 2·2% is the total intensity of the combined transitions.

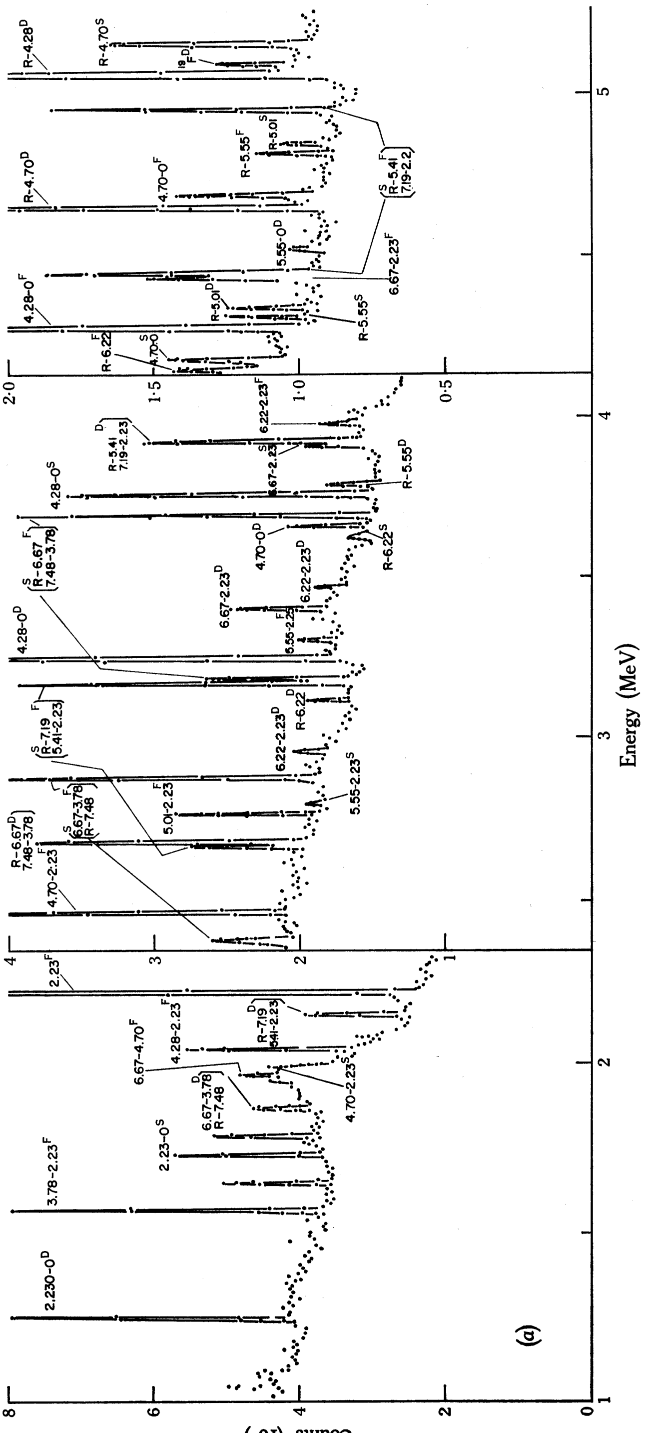
Counts (10³)
Energy (MeV)
(a)
2.230-0D
3.78-2.23F
2.23-0S
6.67-3.78D
R-7.48
6.67-4.70F
4.28-2.23F
R-7.19
5.41-2.23D
4.70-2.23S
2.23F
R-6.67D
7.48-3.78
4.70-2.23F
6.67-3.78F
R-7.48
5.01-2.23F
5.55-2.23S
R-7.19
5.41-2.23F
6.22-2.23D
R-6.22D
4.28-0D
R-6.67
7.48-3.78F
6.67-2.23D
5.55-2.23F
6.22-2.23D
4.70-0D
R-6.22S
4.28-0S
R-5.55D
6.67-2.23S
R-5.41
7.19-2.23D
6.22-2.23F
R-6.22F
4.70-0S
4.28-0F
R-5.01D
R-5.55S
5.55-0D
6.67-2.23F
R-4.70D
4.70-0F
R-5.55F
R-5.01S
R-5.41
7.19-2.2F
R-4.28D
R-4.70S
19FD

Fig. 1a

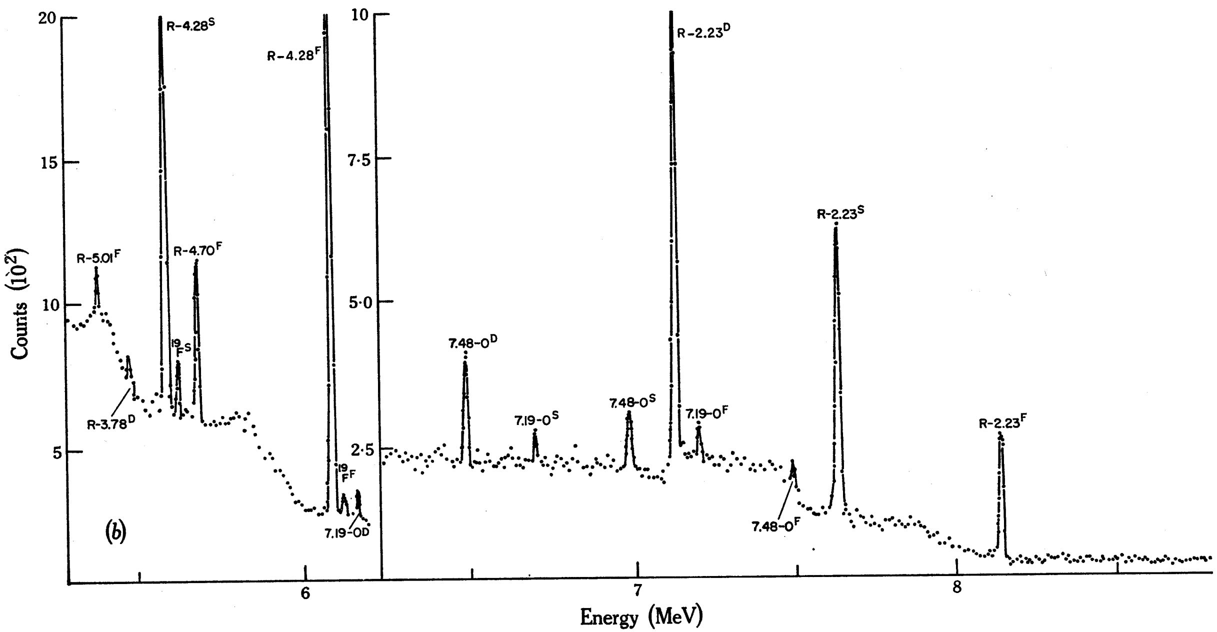

Fig. 1(*a*, *b*). Gamma ray spectrum from the $E_p = 1557$ keV resonance in $^{31}P(p, \gamma)^{32}S$ measured with the 40 cm³ detector. The full energy (F), single escape (S) and double escape (D) peaks for the transitions are labelled. Between the peaks only every fifth point is plotted.

in Paper I. Upper limits were estimated for all unobserved primary transitions to all levels up to and including the 6·67 MeV level, and to higher energy levels where previous authors report transitions which were unobserved in this work. Energies quoted in Table 1 and elsewhere are taken from Coetzee *et al.* (1972), as are the J^π values given. A typical γ-ray spectrum is displayed in Fig. 1.

A recent measurement (O'Brien *et al.* 1975) of the $^{31}P(p, \gamma)^{32}S$ excitation function lists 28 resonances with $E_p < 1 \cdot 75$ MeV. All these were investigated, with the exception of the very weak (<0·02 eV) resonances at 355 and 620 keV, and the weak (<0·3 eV) and broad (4 keV) resonance at 994 keV.

The spectrum of the 1438 keV resonance was measured using both target materials (P and Zn_2P_3) as a spot check on any possible contaminant γ-rays from target constituents other than phosphorus; none was observed.

Measurements of branching ratios of the resonance levels in the energy range considered here have been made by other workers with NaI(Tl) detectors (Kern and Cochran 1956; Andersen *et al.* 1961; Berkes *et al.* 1962; Nelson *et al.* 1962; Chagnon and Treado 1963; Spring 1963; Ter Veld and Brinkman 1963; Andersen 1965; Spring *et al.* 1965; Holmberg 1966), and by workers with Ge(Li) detectors (Piluso *et al.* 1969; Vernotte *et al.* 1969; Holmberg and Viitasalo 1970; Coetzee *et al.* 1972). The most comprehensive of these is the study by Coetzee *et al.* (1972).

Comparison of the present work with previous NaI(Tl) results showed overall good agreement. Some ambiguities present in the decay schemes deduced from Na(Tl) measurements were removed by the present work, and weak components were more easily detected with the Ge(Li) detector.

Comparison of the present work with previous Ge(Li) results showed excellent agreement for most resonances, provided that the errors in the results of Coetzee *et al.* (1972) and Holmberg and Viitasalo (1970) were assumed to be of the same order as those of the present experiment; they quote no errors for their work.

In the list of further comments which follows, note is made of discrepancies with other workers only where the results fall outside two error bars of each other.

Resonance Level at 895 keV

Viitasalo and Forsblom (1974) assign relative intensities of 1% to the branches to the 4·70 and 5·01 MeV levels. The present work, in agreement with Coetzee *et al.* (1972), gives intensities of $5 \cdot 2 \pm 0 \cdot 9$ % and $3 \cdot 0 \pm 1 \cdot 5$ % for these branches. No explanation for the disagreement could be found.

Resonance Level at 1057 keV

Holmberg (1966) reports a strong $R \to 5 \cdot 01 \to 2 \cdot 23$ MeV cascade at this resonance. However, the present results agree with the alternative explanation of Coetzee *et al.* (1972) and Viitasalo and Forsblom (1974) that these γ-rays are mainly due to an $R \to 7 \cdot 12 \to 2 \cdot 23$ MeV cascade. In the present work, it was possible to set an upper limit on the former cascade, of 7%, by putting an upper limit on the weak (2%) secondary transitions of the 5·01 MeV level to the ground state, and by using the known branching ratios of the 5·01 MeV level.

Resonance Levels at 1400 and 1403 keV

It was not possible to resolve these resonances fully, owing to finite level widths and finite beam energy spread. The spectrum of the 1400 keV resonance was measured cleanly by holding the beam energy on the edge of the combined excitation function peak; the target used was sufficiently thick that the 1400 keV resonance formed a clear step on the low energy side. The combined spectrum was also measured, and the effect of the 1400 keV resonance was subtracted by normalizing to the total yields given by O'Brien *et al.* (1975).

Resonance Level at 1411 keV

At this resonance, Coetzee *et al.* (1972) report branches to the 4·46 and 5·01 MeV levels of 3% and 4% respectively, which were not observed in the present work, while they do not report the branches observed here to the 5·41 and 5·55 MeV levels, of strengths 3·2% and 2·5%. This disagreement is probably due to a typographical error in Table 3 of their paper, the intensities for the branches to the 5·41 and 5·55 MeV levels appearing in the columns for the branches to the 4·46 and 5·01 MeV levels. This view finds support in the results of Vernotte *et al.* (1973) and Viitasalo and Forsblom (1974). The decay scheme proposed by Vernotte *et al.* (1969) for the 10·231 MeV level cannot be reconciled with the present work or with Coetzee *et al.*; however, it shows a striking resemblance to the decay scheme of the 10·224 MeV level, and it is probably this level which is being excited in their work.

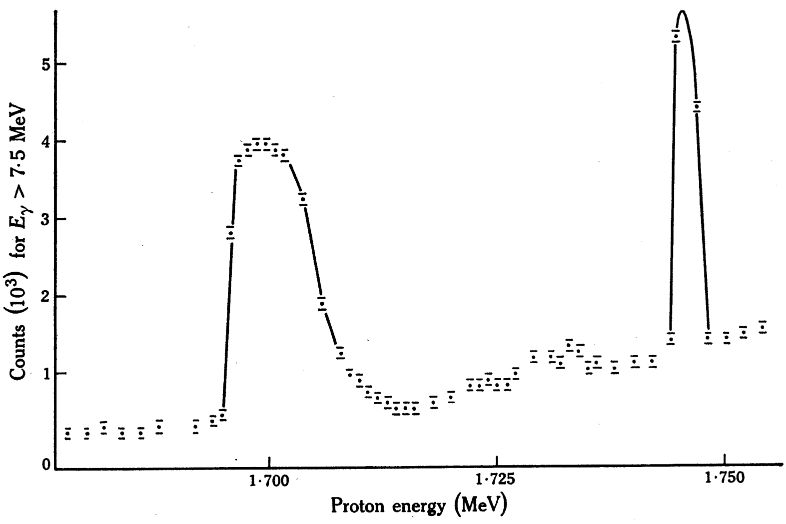

Fig. 2. Excitation function of $^{31}P(p, \gamma)^{32}S$ in the energy range $1675 < E_p < 1755$ keV, for γ-ray energies $E_\gamma > 7 \cdot 5$ MeV.

Resonance Level at 1747 keV

The resonance of total yield 2·9 eV at $E_p = 1747$ keV reported by Coetzee *et al.* (1972) was not observed in the present work. An excitation function of the reaction in the energy range $1675 < E_p < 1755$ keV is displayed in Fig. 2; this was measured using two 12·7×15·3 cm NaI(Tl) crystals by R. O'Brien (personal communication), who observed pulses corresponding to γ-ray energies >7·5 MeV. The peak at $E_p = 1699$ keV corresponds to the resonance of that energy observed by Coetzee *et al.* The width of this resonance is <1 keV (O'Brien *et al.* 1975) so that the width of the 1699 keV peak in Fig. 2 is almost entirely due to the thickness of the elemental phosphorus target used. The peak at 1747 keV is therefore produced by a much thinner target than the phosphorus. Spectra measured at $E_p = 1747$ keV showed strong γ-rays from the reaction $^{13}C(p,\gamma)^{14}N$ which is very strongly resonant at 1748 keV (Ajzenberg-Selove 1970). Gamma rays from $^{12}C(p,\gamma)^{13}N$ were also present in the spectra, produced from the tail of the 1698 keV resonance in that reaction (Ajzenberg-Selove). The narrow peak at $E_p = 1747$ keV in Fig. 2 is therefore attributed to a thin layer of carbon on the front of the target. Clearly no other resonance of any significant strength is present in this energy region. It is concluded that the 1747 keV resonance reported by Coetzee *et al.* was due to ^{13}C, but we are unable to explain the decay scheme they attribute to this resonance; the decay of the $^{13}C(p,\gamma)$ resonance is qualitatively similar to the decay scheme that they propose, but the γ-ray energies differ by nearly 1 MeV.

Table 2. Decay modes of bound levels in ^{32}S

The errors which arise from uncertainties in the peak areas and in the efficiency calibrations are displayed as superscripts

Initial level		Relative intensities for decay to E_f (MeV)							
E_i (MeV)	J_i^π	$E_f = 0$, $J_f^\pi = 0^+$	2·23 2^+	3·78 0^+	4·28 2^+	4·46 4^+	4·70 1^+	5·01 3^-	5·41 3^+
2·23	2^+	**100**							
3·78	0^+	<10	**100**						
4·28	2^+	$\mathbf{87}^{0\cdot5}$	$\mathbf{13}^{0\cdot5}$	<0·4					
4·46	4^+	<1	**100**	<0·3					
4·70	1^+	$\mathbf{39}^{1}$	$\mathbf{61}^{1}$	<0·4	<0·6				
5·01	3^-	$\mathbf{4}^{1}$	$\mathbf{96}^{1}$	<0·04	<0·1				
5·41	3^+	<5	**100**	—	<6	<1	<1	<2	
5·55	2^+	$\mathbf{40}^{1\cdot5}$	$\mathbf{60}^{1\cdot5}$	<1	<1	<2	<1	<0·4	
5·80	1^-	**100**	<5	<1·5	<1	<1·5	<1	<1	
6·22	2^-	<1·5	**100**	<0·8	<1·5	<0·6	<0·5	<2	<0·2
6·62	4^-	<0·3	$\mathbf{3}^{0\cdot3}$	<0·6	<0·2	$\mathbf{24}^{0\cdot7}$	<0·3	$\mathbf{73}^{1}$	<0·9
6·67	$1,2^+$	<3	$\mathbf{37}^{4}$	$\mathbf{49}^{5}$	<7	<3	$(14)^{2}$	<4	<1
6·76	$2^-,3$	$\mathbf{2}^{1}$	<7	<4	<3	$\mathbf{24}^{10}$	<8	$\mathbf{74}^{30}$	<3
6·85		<8	<7	<8	$\mathbf{80}^{10}$	$\mathbf{20}^{10}$	<5	<13	<5
7·00	1^+	<2	**100**	<16	<2	<2	<1	<2	<1
7·12	2^+	$\mathbf{2}^{0\cdot5}$	$\mathbf{86}^{2}$	<1·4	$\mathbf{3}^{1}$	<1	$\mathbf{9}^{1}$	<1	<0·5
7·19	1^+	$\mathbf{41}^{12}$	$\mathbf{59}^{12}$	<55	<35	<54	<25	<28	—
7·48	$1^-,2,3$	**100**	<7	<15	<13	<14	<6	<9	<10
7·54	0^+	<7	<14	<11	<8	<6	**100**	<5	<10
7·70	$2,3,4^+$	<60	**100**	<45	<70	<50	<50	<50	<50
7·95		<0·5	<4	<2	<10	<8	<3	$\mathbf{60}^{10}$	$(40)^{10}$
8·13	1^+	$\mathbf{91}^{6}$	$\mathbf{9}^{6}$	<10	<3	<4	<4	<2	<4

Bound levels

The measured branching ratios of bound levels in ^{32}S excited in this work are displayed in Table 2. The errors (displayed as superscripts) arise from uncertainties in the peak areas and in the relative efficiency curves. Upper limits were found for all unobserved transitions in the energy range of the spectrum, and those not displayed in Table 2 may be seen in Table 3. The results of the present work are in general agreement with previous observations (Andersen *et al.* 1961; Berkes *et al.*

Table 3. Upper limits on unobserved decay modes of bound levels in ^{32}S

The upper limits are expressed as a percentage of the total decay of each level

E_i (MeV)	Upper limits for decay to E_f (MeV) $E_f = 5\cdot55$	5·80	6·22	6·62	6·67	6·76	6·85	7·00	7·12	7·19	7·48	7·54
6·22	0·2											
6·62	0·2	0·1										
6·67	2	1										
6·76	1	2										
6·85	7	3	3									
7·00	1	9	0·5									
7·12	1	0·3	0·3									
7·19	30	11	3	7	16							
7·48	10	7	7	7	3	3	3					
7·54	9	5	4	3	6	3	10	2	5	2		
7·70	40	40	30	25	25	50	15	15	15	15		
7·95	6	6	10	2	5	2	1	1	1	—	1	
8·13	4	1	2	3	3	9	2	3	0·6	0·7	0·6	0·6

Table 4. Comparison of results with previous work

The present results for branching ratios are compared with those of: C, Coetzee *et al.* (1972); M, Moss *et al.* (1973); P, Piluso *et al.* (1969); V, Viitasalo and Forsblom (1974)

Bound level E_i (MeV)	E_f (MeV)	Branching ratios (%) Present	C	M	P	V
4·70	0	39±1	39±3	39	44	45±3
	2·23	61±1	61±3	61	56	55±3
6·67	0	<3	<6	<6	—	—
	2·23	37±4	(50)	53±5	51	—
	3·78	49±5	(50)	47±5	49	—
	4·70	(14±2)	—	<15	—	—
6·76	0	2±1	3±2	<5	—	—
	2·23	<7	<25	<5	—	—
	4·46	24±10	—	<26	—	—
	5·01	74±30	(97)	100	—	—
7·12	0	2±0·5	4±3	11±3	—	7±3
	2·23	86±2	92±5	81±4	—	80±10
	3·78	<1·4	<5	<3	—	3±2
	4·28	3±1	4±3	<5	—	3±2
	4·46	<1	—	8±4	—	—
	4·70	9±1	—	<14	—	7±3
7·95	4·46	<8	<10	—	(43)	—
	5·01	60±10	65	—	(57)	—
	5·41	(40±10)	—	—	—	—
	Unknown	—	35	—	—	—

1962; Nelson *et al.* 1962; Chagnon and Treado 1963; Spring 1963; Ter Veld and Brinkman 1963; Andersen 1965; Spring *et al.* 1965; Holmberg 1966; Poletti and Grace 1966; Garvey *et al.* 1969; Piluso *et al.* 1969; Forsblom *et al.* 1970; Coetzee *et al.* 1972; Leccia *et al.* 1972; Moss *et al.* 1973; Vernotte *et al.* 1973; Viitasalo and Forsblom 1974). A comparison between previous and present work is shown for a number of levels in Table 4. The decays of some of the levels require further comment.

Bound Level at 4·70 MeV

The present result of branches of 39 ± 1 % and 61 ± 1 % to the ground and 2·23 MeV levels is in agreement with the results of Coetzee *et al.* (1972) but not with the results of Viitasalo and Forsblom (1974) and Piluso *et al.* (1969) of 45 ± 3 % and 55 ± 3 %, and 44% and 56% respectively. The present results quote the smallest errors.

Bound Level at 6·67 MeV

The branch to the 4·70 MeV level, proposed in this work, is tentative as it was observed at only one resonance (E_p = 1557 keV).

Coetzee *et al.* (1972) have noted that the decay to the 3·78 MeV level coincides with a weak $R \to 7\cdot48$ MeV transition. In view of this, and the fact that they observed the 6·67 MeV level to be excited at only one resonance, they label the $6\cdot67 \to 3\cdot78$ MeV transition as uncertain. In the present work, the 6·67 MeV level was observed to be excited at the 1016, 1403 and 1557 keV resonances, and the intensity of the $6\cdot67 \to 3\cdot78$ MeV transition was estimated by subtracting from the combined peak area the contribution of the transition from the resonance to 7·48 MeV, estimated from the decay branches of the 7·48 MeV level.

Bound Level at 6·76 MeV

The decay of this level to the 5·01 MeV level was obscured by the double escape peak of the $5\cdot01 \to 2\cdot23$ MeV transition. Coetzee *et al.* (1972) assume that the $6\cdot76 \to 5\cdot01$ MeV decay accounts for all the decay of this level not proceeding to the ground state. The 24% branch to the 4·46 MeV level, proposed in this work, was observed at the 888, 1438 and 1583 keV resonances.

Bound Level at 7·12 MeV

The branch to the 4·46 MeV (4^+) level proposed by Moss *et al.* (1973) is not consistent with either the present work or that of Coetzee *et al.* (1972). No explanation could be found for this discrepancy. The present work proposes a 9% decay to the 4·70 MeV level. This transition, which was observed at the 1016, 1057, 1400 and 1699 keV resonances, is not reported by Coetzee *et al.*, but finds support in the results of Viitasalo and Forsblom (1974).

Bound Level at 7·48 MeV

Coetzee *et al.* (1972) propose (tentatively) a 30% decay of this level to the 3·78 MeV level, on the basis that the decay of the level is not fully accounted for by the ground state branch, and that the branch to the 3·78 MeV level is hidden (by the transition from the 1557 keV resonance to the 6·67 MeV level). The upper limit in the present work (of 15%) was derived from the spectrum of the 1151 keV resonance, where no such obscuration occurs.

Bound Level at 7·95 MeV

This work agrees with previous findings (Piluso *et al.* 1969; Coetzee *et al.* 1972; Leccia *et al.* 1972) that the decay of the 7·95 MeV level is largely (~60%) to the 5·01 MeV level. Piluso *et al.* and Leccia *et al.* report a transition of ~40% to the 4·46 MeV level; in the present work (as in Coetzee *et al.*) this was interpreted as the $R \rightarrow 6\cdot76$ MeV transition occurring at the 1438 keV resonance. The 7·95→4·46 MeV transition was not observed when the 7·95 MeV level was excited via the 1583 keV resonance (an upper limit of 8% was estimated for it here). Coetzee *et al.* give no suggestion for the remaining ~40% excitation of the 7·95 MeV level. A possible transition to the 5·41 MeV level is proposed in the present work, but this transition is tentative because it was not clearly resolved from other spectral components.

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