Aust. J. Phys., 1975, **28**, 155–62

Total Yield Measurements in $^{31}P(p,\gamma)^{32}S$

R. O'Brien,[A,B] *Z. E. Switkowski,*[A,C] *A. K. Smith*[A] *and D. G. Sargood*[A]

[A] School of Physics, University of Melbourne, Parkville, Vic. 3052.
[B] Present address: State College of Victoria at Melbourne, Parkville, Vic. 3052.
[C] Present address: California Institute of Technology, Pasadena, California, U.S.A.

Abstract

The reaction $^{31}P(p,\gamma)^{32}S$ has been investigated in the proton energy range 0·33–1·75 MeV. Total γ-ray strengths were determined for 28 resonances. Yield curves were measured over limited portions of the energy range, which between them covered the whole range. An estimate of the nonresonant cross section was obtained, and total resonance widths were deduced.

Introduction

The cosmic abundances of the elements from ^{20}Ne to ^{31}P (omitting ^{28}Si) have been attributed by Arnett (1969, 1971) and Woosley *et al.* (1973) to explosive carbon burning in the carbon-rich shells of massive stars at the onset of supernova explosions. Amongst these nuclei, ^{31}P stands out as the only one whose relative abundance has not been predicted to within a factor of two of the observed solar system ratios, it being low by a factor of four. According to the compilation of Clayton and Woosley (1973), the two most important reactions determining the abundance of ^{31}P are $^{28}Si(\alpha,p)^{31}P$ and $^{31}P(p,\gamma)^{32}S$. It is therefore necessary to know the cross sections of these reactions over the range of energies that is important at the temperature of the explosion, believed to be $\sim 2\times 10^9$ K. The energy range of interest for the reaction $^{31}P(p,\gamma)^{32}S$ is 0·6–1·8 MeV.

Previous measurements of resonance strengths in the reaction $^{31}P(p,\gamma)^{32}S$ have been made by various authors (Paul *et al.* 1955; Berkes *et al.* 1962; Chagnon and Treado 1963; Spring 1963; Ter Veld and Brinkman 1963; Smulders 1964; Andersen 1965; Spring *et al.* 1965; Engelbertink and Endt 1966; Vernotte *et al.* 1973) over limited energy ranges, the only comprehensive measurements being those of Coetzee *et al.* (1972) who made relative yield measurements on resonances in the energy range 355–2027 keV. The present work consists of absolute measurements of the resonance strengths and of the nonresonant yield, in the energy range 330–1750 keV.

Experimental Details

The detection system, experimental arrangement and procedure were the same as those described by Switkowski *et al.* (1975, present issue pp. 141–53; referred to hereafter as Paper I) with the exception that excitation functions were measured for the two γ-ray energy ranges 3·0–12·0 and 7·5–12·0 MeV (requiring an additional scaler channel). The 7·5–12·0 MeV window count was used in the final analysis only when the contamination reaction $^{19}F(p,\alpha\gamma)^{16}O$ rendered the spectrum below 7·5 MeV doubtful.

Targets were prepared from 99·999% pure elemental red phosphorus (obtained from Research Organic–Inorganic Chemical Corp., Sun Valley, California), using the deposition process described by Hooton (1964) in which red phosphorus is deposited from a strongly heated phosphorus atmosphere produced initially by evaporation. (Direct evaporation would produce unstable yellow phosphorus targets.) Targets were deposited on cleaned and baked tantalum or gold blanks, and were found to be durable under extended proton bombardment.

Measurement of Resonance Strengths

Semi-thick Target Measurements

At 17 of the 28 resonances in the energy range studied, the resonance width and spacing permitted measurements to be made using semi-thick targets. Excitation functions were measured using 1–2 keV intervals, and γ-ray spectra were collected at each point. The total charge collection per point varied from 50 μC for relatively strong resonances to 300 μC for some weak ones. Beam currents between 0·4 and 4 μA were used, depending on count rate.

The method used for obtaining the spectrum shape for each resonance differed from that described in Paper I only in the procedure for extrapolating the spectrum to zero energy. For most resonances, the lowest energy γ-ray was 2·23 MeV, corresponding to the first-excited-state to ground-state transition in ^{32}S. Enough of the spectrum could be recorded to enable direct extrapolation of the spectrum of this and higher energy γ-rays, based on a collection of mono-energetic line shapes. When lower energy γ-rays were present, these were handled by the photofraction techniques described in Paper I. For this purpose, several photofractions were measured over the relevant range of energies. In addition to the 1·37 MeV photofraction measurement of $0{\cdot}57 \pm 0{\cdot}07$ given in Paper I, the 1·78 MeV photofraction was measured as $0{\cdot}41 \pm 0{\cdot}06$ by the same method, using the 633 keV resonance in ^{27}Al(p,γ)^{28}Si. Also, the 1·63 MeV photofraction was found to be $0{\cdot}47 \pm 0{\cdot}04$ by direct extrapolation of the clean line shape, obtained at the strong resonance at 1163 keV in ^{23}Na(p,$\alpha\gamma$)^{20}Ne. From the extrapolation procedure for resonances with no γ-rays of energy lower than 2·23 MeV, the 2·23 MeV photofraction was shown to be $0{\cdot}37 \pm 0{\cdot}07$. From this collection of photofractions, it was possible to obtain all photofractions needed in the analysis. Errors incurred via the extrapolation procedure contributed errors in N_i, the total number of interactions in the crystals corresponding to the step in the yield function. Such errors in N_i are estimated to be always less than $\pm 5\%$ and typically less than $\pm 2\%$.

The step in the semi-thick target excitation function was found from the relation (equation (1) of Paper I)

$$y(\infty, \infty) = N_i/\varepsilon_t ,$$

where ε_t is the total detection efficiency discussed in Paper I (where it is defined by equation 2). The branching ratios required for the evaluation of ε_t for particular resonances were taken from the work of Coetzee *et al.* (1972). The value of the total detection efficiency is insensitive to errors in the branching ratios, particularly if decay of the resonance is not predominantly by direct ground state transition. Since most excited states of ^{32}S have complicated decay schemes, uncertainties in

branching ratios seldom made significant contributions to the quoted errors for resonance strengths. For resonance strength calculations based on equation (3) of Paper I, values for the atomic stopping power ξ were obtained from the compilation of Marion and Young (1968), interpolating as necessary.

Thin Target Measurements

To permit the determination of the relative strengths of resonances (particularly those which were not amenable to semi-thick target measurement), thin target excitation functions were measured over limited energy ranges, the sum of which

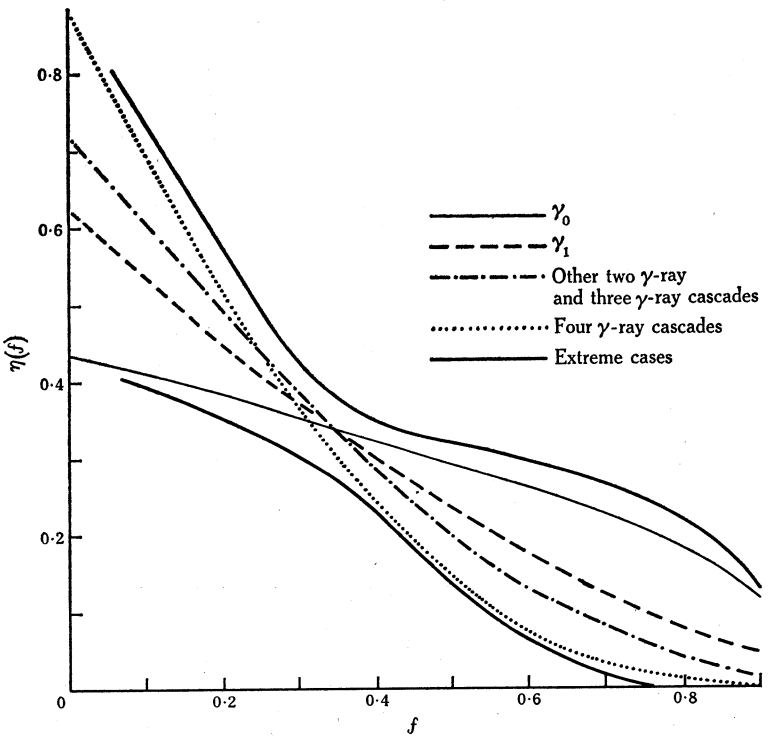

Fig. 1. Typical curves of partial detection efficiency η as a function of the fraction f of excitation energy. Dominant decay modes are indicated in the legend in the diagram. The thick full curves represent the extreme values of η obtained from all resonances surveyed. The other curves represent averages obtained from many resonances each of which had a common dominant decay mode.

covered the complete energy range 0·33–1·75 MeV. Elemental targets were used, different ones being employed in different energy ranges. The resonance at 642 keV was traced out with every target used, and all resonance strengths deduced from the yield curves were referred to this resonance as standard. Proton energy steps of 1–2 keV were adopted in tracing out the resonances, and larger steps were used in regions where no resonances occurred. The total charge collection was in general 150 μC per point but longer runs were made on some weak resonances with complex γ-ray spectra. Measurements were made using a single target spot, and repeated tracing of a reference resonance provided a check against target deterioration.

A set of partial detection efficiency curves (defined in Section 4*b* of Paper I) was plotted for the reaction $^{31}P(p,\gamma)^{32}S$ using information from the spectra of resonances for which decay schemes are known. A representative set of such curves is shown in Fig. 1. The partial detection efficiency $\eta(f)$ had the same value for all decay schemes for $f = 0{\cdot}34$, this common value being $\eta(0{\cdot}34) = 0{\cdot}34 \pm 0{\cdot}03$.

Table 1. Resonances in reaction $^{31}P(p,\gamma)^{32}S$

Resonance energy[A] E_r (keV)	Method of analysis Thick target	Thin target	Resonance strength $(2J_r+1)\Gamma_p\Gamma_\gamma/\Gamma$ (eV)	Width[B] Γ (keV)
355	Yes	Yes	0·017±0·002	
439	Yes	No	0·13 ±0·02	
541	Yes	Yes	0·51 ±0·06	
620	Yes	No	0·006±0·004	
642	Yes	Standard	0·25 ±0·03	
811	Yes	Yes	1·06 ±0·11	
821	Yes	Yes	0·23 ±0·04	
874	No	Yes	0·06 ±0·02	~1
888	No	Yes	0·034±0·017	
895	No	Yes	0·31 ±0·07	
984	Yes	Yes	0·091±0·014	
994±3	No	Yes	<0·3	4·0±0·8
1016±3	No	Yes	0·031±0·009	
1057	Yes	Yes	0·55 ±0·06	
1090	No	Yes	0·19 ±0·06	
1121	Yes	Yes	1·04 ±0·13	
1151	Yes	Yes	1·85 ±0·22	
1155	Yes	Yes	0·66 ±0·08	
1251	Yes	Yes	4·6 ±0·6	1·5±0·8
1400	No	Yes	0·7 ±0·2	
1403	No	Yes	2·0 ±0·6	
1411	No	Yes	0·5 ±0·1	
1438	Yes	Yes	4·8 ±0·6	
1473	Yes	Yes	1·2 ±0·2	
1515±3	No	Yes	0·8 ±0·2	5·8±1·2
1557	Yes	Yes	4·2 ±0·5	
1583	Yes	Yes	4·6 ±0·6	
1699	No	Yes	0·70 ±0·15	

[A] Values are taken from Coetzee *et al.* (1972) except at 944, 1016 and 1515 keV.
[B] All widths are <1 keV unless otherwise shown.

It was necessary to use partial detection efficiencies for analysis of the spectra of the resonances at 874, 888, 1016 and 1515 keV because of lack of information about the decay scheme; the value $f = 0{\cdot}34$ being used in this analysis. It was necessary to use this method of analysis also for the 994 keV resonance because the contamination reaction $^{19}F(p,\alpha\gamma)^{16}O$ made the spectrum below 7·5 MeV unusable. The value of f for this measurement was 0·76.

For overlapping resonances the fitting procedure described in Paper I was used. A very good fit to the experimental function was obtained on the assumption that the elemental targets were uniform (that is, $n(x)$ = const. in equation (6) of Paper I). The theoretical fit to the experimental excitation function was used to determine relative resonance strengths and also to infer resonance widths or upper limits.

Results

Resonance Strengths

The results of the resonance strength measurements are shown in Table 1. No attempt was made to make accurate determinations of resonance energies, the quoted

values being those of Coetzee *et al.* (1972) except for the resonances at 994, 1016 and 1515 keV, which were not studied by them.

Table 2. Comparison of data from P and Zn_3P_2 targets

Resonance energy E_r (keV)	Resonance strength $(2J_r+1)\Gamma_p\Gamma_\gamma/\Gamma$ (eV) P target	Zn_3P_2 target
642	0·25±0·03	0·27±0·03
1121	1·04±0·13	1·14±0·15
1583	4·6 ±0·6	4·7 ±0·8

Fifteen resonances were investigated using both semi-thick and thin target techniques. The relative strengths as determined by the two methods were in agreement to within the uncertainties for both the measured peak areas and the γ-ray spectrum total counts N_i, giving a good check on internal consistency. The thin target data have been normalized to the semi-thick target value of 0·25 ± 0·03 eV for the 642 keV resonance, which resonance was accessible to both accelerators used. Semi-thick target measurements were also made on the resonances at 642, 1121 and 1583 keV, using targets of Zn_3P_2 evaporated onto 0·025 cm gold backings. The strengths obtained from these measurements and those using elemental targets are given in Table 2. The agreement is most satisfactory.

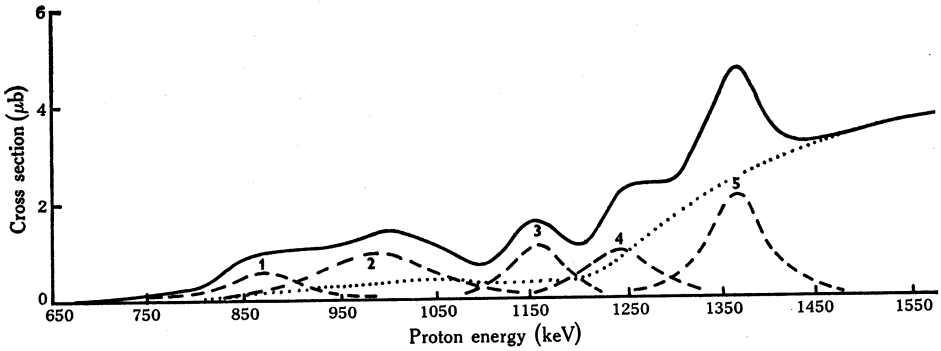

Fig. 2. Unresolved cross section (full curve), with the more obvious resonant components (numbered dashed curves) and the residue (dotted curve).

Unresolved Yield

The γ-ray yield remaining after extraction of the narrow resonances represents the contribution of very broad resonances and of nonresonant proton capture. In measurements using a 40 cm^3 Ge(Li) detector, S. G. Boydell (personal communication) found that, at several proton energies in the region of interest, the off-resonance γ-ray yield arises mainly from ground state transitions. The partial detection efficiency η for such decay was therefore used to determine the total γ-ray yield. This yield was converted to a cross section, using the target thickness value determined by the excitation function fitting procedure used on the narrow resonances. This cross section is shown by the full line in Fig. 2. It appears to consist mainly of five broad overlapping resonances (dashed lines) which are numbered in the diagram. The

dotted line, which shows the residue after subtraction of these broad resonances, displays no resonant behaviour up to 1200 keV.

The γ-ray detector window corresponding to the energy range 7·5–12 MeV was used in determining this unresolved yield, thereby eliminating any contributions from common contaminant reactions such as $^{19}F(p,\alpha\gamma)^{16}O$ and $^{15}N(p,\alpha\gamma)^{12}C$. All these broad underlying resonances and the truly nonresonant yield are therefore attributed to $^{31}P(p,\gamma)^{32}S$. The energies, strengths and widths of the resonances shown in Fig. 2 are listed in Table 3.

Table 3. Broad unresolved resonances in reaction $^{31}P(p,\gamma)^{32}S$

Resonance energy[A] E_r (keV)	Excitation energy[A] (MeV)	Resonance strength[B] $(2J_r+1)\Gamma_p\Gamma_\gamma/\Gamma$ (eV)	Width[C] Γ (keV)
875	9·713	0·045	95
995	8·829	0·140	140
1150	9·978	0·098	60
1250	10·076	0·095	80
1360	10·183	0·178	60

[A] Errors in energies are ±10 keV.
[B] Strengths are considered reliable to within a factor of two.
[C] Errors in widths are ±10%.

Discussion

The present values obtained for resonance strengths are compared in Table 4 with those reported by previous authors. With the exception of the very weak resonances at 355, 620, 874 and 888 keV, the relative strengths obtained in the present work are in agreement with those of Coetzee *et al.* (1972) up to 1700 keV, and with those of Vernotte *et al.* (1973). However, these authors normalized their results to the value obtained by Engelbertink and Endt (1966) of 0·52 eV for the 642 keV resonance, which is greater than our value by a factor of two. Consequently the strengths reported in the present paper are approximately one-half of those reported by Coetzee *et al.* and Vernotte *et al.* The overall agreement of the results of Paul *et al.* (1955) and Andersen (1965) with those of Coetzee *et al.* and Vernotte *et al.* lends support to the value obtained by Engelbertink and Endt for the 642 keV resonance, whilst our value is supported by the work of Ter Veld and Brinkman (1963) and of Smulders (1964).

We also made measurements on four resonances in $^{27}Al(p,\gamma)^{28}Si$. These measurements, made with elemental targets and the identical experimental arrangement as used for the $^{31}P(p,\gamma)$ measurements, gave results in excellent agreement with those of Lyons *et al.* (1969). (The comparison is shown in Table 2 of Paper I.) This agreement, together with that between the measurements made with elemental P and Zn_3P_2 targets, listed in the present Table 2, gives additional support to the present results.

The resonance strengths in different nuclei, reported by Engelbertink and Endt (1966), are linked by relative yield measurements using chemical compound targets, each containing two of the nuclei studied. The nuclei ^{23}Na, ^{31}P and ^{32}S form a self-consistent triplet in that they were all linked in pairs. However, the strength (Paper I) for the 512 keV resonance in $^{23}Na(p,\gamma)$ is only 19% below the value of

Engelbertink and Endt and is in agreement within the combined experimental errors, whilst the strength (reported here) of the 642 keV resonance in $^{31}P(p,\gamma)$ is 52% lower than their value. There is therefore disagreement between the present results and those of Engelbertink and Endt for both the absolute strength of the $^{31}P(p,\gamma)$ resonance and the relative strengths of the $^{31}P(p,\gamma)$ and $^{23}Na(p,\gamma)$ resonances.

Table 4. Comparison of results for $(2J_r+1)\Gamma_p\Gamma_\gamma/\Gamma$

E_r (keV)	Present results	Resonance strength (eV)* CMR	VGLM	EE	S & SHJ	A	CT	PGHB	TVB	S
355	0·017±0·002	0·003					0·012		0·019±0·005	
439	0·13 ±0·02	0·25					0·135		0·16 ±0·03	
541	0·51 ±0·06	1·0					0·30			
620	0·006±0·004	0·06								0·003
642	0·25 ±0·03	(0·52)	(0·52)	0·52±0·08	0·36±0·18					0·23
811	1·06 ±0·11	2·2			1·9 ±0·4			2·88		
821	0·23 ±0·04	0·43						0·49		
874	0·06 ±0·02	0·29								0·03
888	0·034±0·017	0·18								
895	0·31 ±0·07	0·7								
984	0·091±0·014	0·18								
1057	0·55 ±0·06	1·1								
1090	0·19 ±0·06	0·38								
1121	1·04 ±0·13	3·0			1·6 ±0·4			2·44		
1151	1·85 ±0·22	3·0			4·2 ±0·9	5·2±1·2				
1155	0·66 ±0·08	1·5								
1251	4·6 ±0·6	11	11·8			8·0±1·6				
1400	0·7 ±0·2	1·3	1·3							
1403	2·0 ±0·6	5·0	3·8							
1411	0·5 ±0·1	2·0	1·0							
1438	4·8 ±0·6	11	8·3			12·0±2·8				
1473	1·2 ±0·2	2·4	1·9			2·0±0·8				
1557	4·2 ±0·5	9	8·7		3·2	9·2±2·0				
1583	4·6 ±0·6	8	7·9		3·3	10·0±2·4				
1699	0·70 ±0·15	0·9			<0·28					

* Notes on results:
CMR = Coetzee *et al.* (1972); all values relative to 0·52 eV at the 642 keV resonance; stated errors ±30%.
VGLM = Vernotte *et al.* (1973); all values relative to 0·52 eV at the 642 keV resonance; stated errors ±20%.
EE = Engelbertink and Endt (1966).
S & SHJ = Spring (1963) and Spring *et al.* (1965).
A = Andersen (1965).
CT = Chagnon and Treado (1963).
PGHB = results are from γ_0 and γ_1 yields of Paul *et al.* (1955) corrected by means of branching ratios from Coetzee *et al.* (1972).
TVB = Ter Veld and Brinkman (1963).
S = Smulders (1964).

The link between the $^{31}P(p,\gamma)$ and $^{23}Na(p,\gamma)$ resonances as measured by Engelbertink and Endt (1966) depends on an accurate knowledge of the stoichiometric ratios in the $Na_4P_2O_7$ target used, whereas the present results depend on measurements made with elemental targets and are therefore to some extent more fundamental. However, for departure of the stoichiometric ratios from those implied by the formula $Na_4P_2O_7$ to be the cause of the disagreement, it would be necessary for compensating departures to have occurred in the P_4S_6 and $Na_2S_2O_7$ targets used for the $^{31}P(p,\gamma)$–$^{32}S(p,\gamma)$ and $^{23}Na(p,\gamma)$–$^{32}S(p,\gamma)$ links, since Engelbertink and Endt reported internal consistency between these three links. We are therefore unable at this time to provide any convincing explanation for the disagreement.

Coetzee *et al.* (1972) also reported a resonance at 1747 keV with a strength of 2·9 eV. A weak resonance at this energy was seen in the present work but it is

clearly not due to $^{31}P(p,\gamma)^{32}S$ since the width of the peak in the excitation function was much less than that due simply to the thickness of the P target. It is therefore produced by a target much thinner than the P target and is attributed to a contaminant layer on the surface. There is a strong resonance at 1748 keV in $^{13}C(p,\gamma)^{14}N$ and this seems the most likely origin of this peak.

Acknowledgments

We would like to thank Dr J. R. Bird for the hospitality of the Australian Atomic Energy Commission Laboratory. The work was supported in part by the Australian Institute for Nuclear Science and Engineering.

References

Andersen, S. L. (1965). *Phys. Norv.* **1**, 247.
Arnett, W. D. (1969). *Astrophys. J.* **157**, 1369.
Arnett, W. D. (1971). *Astrophys. J.* **166**, 153.
Berkes, I., Dezsi, I., Fodor, I., and Keszthelyi, L. (1962). *Nucl. Phys.* **39**, 631.
Chagnon, P. R., and Treado, P. A. (1963). *Nucl. Phys.* **40**, 195.
Clayton, D. D., and Woosley, S. E. (1973). Proc. Int. Conf. on Nuclear Physics, Munich, Vol. 2 (Eds J. De Boer and H. J. Mang), p. 717 (North–Holland: Amsterdam).
Coetzee, W. F., Meyer, M. A., and Reitmann, D. (1972). *Nucl. Phys.* A **185**, 644.
Engelbertink, G. A. P., and Endt, P. M. (1966). *Nucl. Phys.* **88**, 12.
Hooton, B. W. (1964). *Nucl. Instrum. Methods* **27**, 338.
Lyons, P. B., Toevs, J. W., and Sargood, D. G. (1969). *Nucl. Phys.* A **130**, 1.
Marion, J. B., and Young, F. C. (1968). 'Nuclear Reaction Analysis'. (North–Holland: Amsterdam).
Paul, E. B., Gove, H. E., Litherland, A. E., and Bartholomew, G. A. (1955). *Phys. Rev.* **99**, 1339.
Smulders, P. J. M. (1964). *Physica (Utrecht)* **30**, 1197.
Spring, E. (1963). *Commentat. Phys.–Math.* **28**, No. 6.
Spring, E., Holberg, P., and Junger, H. (1965). *Commentat. Phys.–Math.* **31**, No. 1.
Switkowski, Z. E., O'Brien, R., Smith, A. K., and Sargood, D. G. (1975). *Aust. J. Phys.* **28**, 141.
Ter Veld, L. K., and Brinkman, N. (1963). *Nucl. Phys.* **40**, 438.
Vernotte, J., Gales, S., Langevin, M., and Maison, J. M. (1973). *Nucl. Phys.* A **212**, 493.
Woosley, S. E., Arnett, W. D., and Clayton, D. D. (1973). *Astrophys. J. Suppl. Ser.* **26**(231), 231.

Manuscript received 19 November 1974