GAMMA RAY DECAY SCHEMES OF LEVELS AT INTERMEDIATE ENERGIES IN ^{32}S

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Abstract

The reaction ^{32}S(p, p′γ)^{32}S has been studied with a 12·7 cm by 10·2 cm NaI(Tl) γ-ray detector in conjunction with a 61 cm double-focusing magnetic spectrometer to determine the γ-ray decay schemes of all known levels in ^{32}S between the excitation energies of 5·40 and 7·15 MeV.

I. Introduction

Several models have been proposed to account for levels in the intermediate excitation energy range (5–9 MeV) in ^{32}S. Among the calculations appropriate to positive parity levels in this range are those of Wildenthal *et al.* (1971), who have performed shell-model calculations for excitation energies up to about 6 MeV, and Castel *et al.* (1971), who consider the coupling of the $J^\pi = 2^+$ one-phonon state to particle–hole excitations for energies up to about 8 MeV. For negative parity levels, a model involving the coupling of a quadrupole phonon and an octupole phonon to give states with $J^\pi = 1^-, 2^-, 3^-, 4^-$, and 5^- in the region of excitation energy $E_x = 7$ MeV has been proposed by Mermaz *et al.* (1969) and Gardner *et al.* (1972).

Because of the high level density in this intermediate excitation energy range, the above models require the accumulation of much information before they can be tested effectively. Prior to the work described herein, there were some notable uncertainties about γ-ray branching ratios of levels in the region (see Section IV and Table 1). In this paper measurements of the γ-ray decay schemes of all known levels in ^{32}S between $E_x = 5·40$ and $7·15$ MeV are reported. The technique employed is the same as that previously used to study ^{27}Al by Elliott *et al.* (1968*b*) and ^{29}Al by Kean *et al.* (1969).

II. Experimental Procedure

Beams of protons from the Australian National University EN tandem accelerator were used to populate states in ^{32}S via the reaction ^{32}S(p, p′γ)^{32}S. A separate particle–gamma coincidence measurement was made for each level of interest. The beam energies ranged from 8·03 to 9·17 MeV (see Fig. 1), and were selected by

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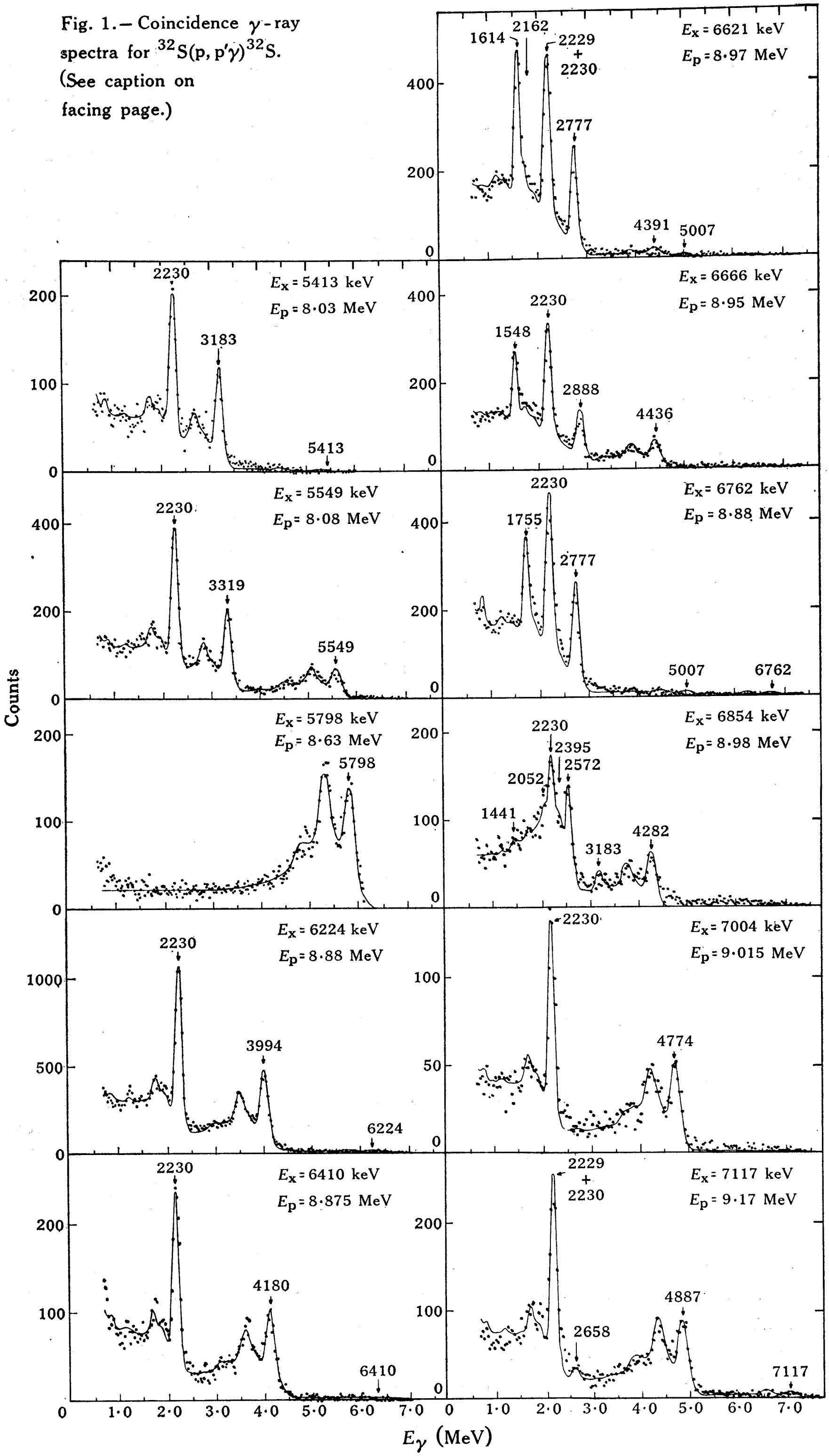
measuring brief excitation functions for each proton group. The target consisted of approximately 100 $\mu g\,cm^{-2}$ of cadmium sulphide (containing natural sulphur) evaporated onto 100 $\mu g\,cm^{-2}$ gold foil. Protons were detected in a 5 cm long by 6 mm wide position-sensitive detector at the focal plane of a 61 cm double-focusing magnetic spectrometer described by Elliott *et al.* (1968*a*). The detector surface was covered with a layer of 6 μm aluminium foil to absorb any α-particles which might also be present. Gamma rays were detected at 90° in a 12·7 cm (diam.) by 10·2 cm (length) NaI(Tl) crystal mounted with its axis vertical and its front face 4·1 cm above the target spot; a 1·6 mm thick steel plate supported the crystal in the top of the target chamber. The proton beam was stopped in a beam dump 3 m from the target. The structure of the target chamber required that the magnetic spectrometer be set at 90°. Accumulation times for the coincidence spectra shown in Figure 1 ranged from 4 to 60 hr.

Standard crossover timing circuits were used for the particle–gamma coincidence measurements. A time-to-amplitude converter (TAC) spectrum was stored in 256 channels of a pulse-height analyser for use in calculating the ratio of real to random coincidences, the width of the time peak being approximately 80 ns (FWHM). The coincidence γ-ray spectrum, gated by a window on the position spectrum and by a 400 ns wide window on the time spectrum, was stored in 256 channels in a second pulse-height analyser.

The coincidence γ-ray spectra were analysed on a Univac 1108 computer using a line-shape fitting program previously described by Elliott *et al.* (1968*b*) and Ophel (1971). Where appropriate, corrections were made for the summing of cascade γ-rays, assuming isotropic angular distributions. The uncertainties in the summing corrections resulted in considerable uncertainties in the intensities of weak ground-state branches. For a triple cascade such as the one from the 6762 keV level, the most important corrections were the three possible double-sum corrections (the triple-sum correction is very small and has been ignored). Each spectrum was also corrected for random coincidences ($\sim 10\%$) either by treating the singles spectrum as a component in the line-shape fitting program, or by subtracting a singles spectrum with an intensity normalization deduced from the measured ratio of real to random coincidences. Except for the ground-state transitions noted below, upper limits for the intensities of unobserved branches were determined by adding line shapes of the appropriate energies to the fitted spectrum and noting by visual inspection the intensities at which these extra components changed the fit significantly. For the ground-state transitions from the 5413, 6224, 6410, and 6762 keV levels, line shapes for the ground-state γ-rays were specified as components in the fits and the resulting intensities plus their errors as calculated by the program were used as upper limits.

Fig. 1 (*opposite*).—Coincidence γ-ray spectra for various levels of ^{32}S populated via the reaction $^{32}S(p, p'\gamma)^{32}S$. For the spectra from all of the levels except the 5798 and the 6854 keV levels, a calculated sum spectrum has been subtracted from the data and the random coincidences have been treated as a component in the fit, as described in the text. For the spectra from the 5798 and the 6854 keV levels, no such sum correction has been made, and a singles line shape of intensity calculated from the ratio of real to random coincidences in the TAC spectrum has been subtracted from the data. For the 5413, 6224, 6410, and 6762 keV levels, the ground-state component shown in the fit was used only to estimate an upper limit.

Fig. 1.— Coincidence γ-ray spectra for ^{32}S(p, p′γ)^{32}S. (See caption on facing page.)



III. Results

Coincidence γ-ray spectra for all of the levels studied are shown in Figure 1. The data for the 5798 keV level have been reported previously (Gardner *et al.* 1972) but are included here for the sake of completeness. The full curves represent the fits to the data obtained from the line-shape analysis. The magnetic spectrometer made the resolution of the various levels and the identification of the particles as protons very easy, so that contributions to each spectrum from ^{32}S levels other than the one of interest are negligible. No evidence was found for contributions from contaminant reactions. The inclusion in the spectra of ground-state components for the 5413, 6224, 6410, and 6762 keV levels improved the fits slightly; however, the intensities of these components were used only to determine upper limits because it was considered that adding these components only compensated for inaccuracies in the corrections for summing and random coincidences.

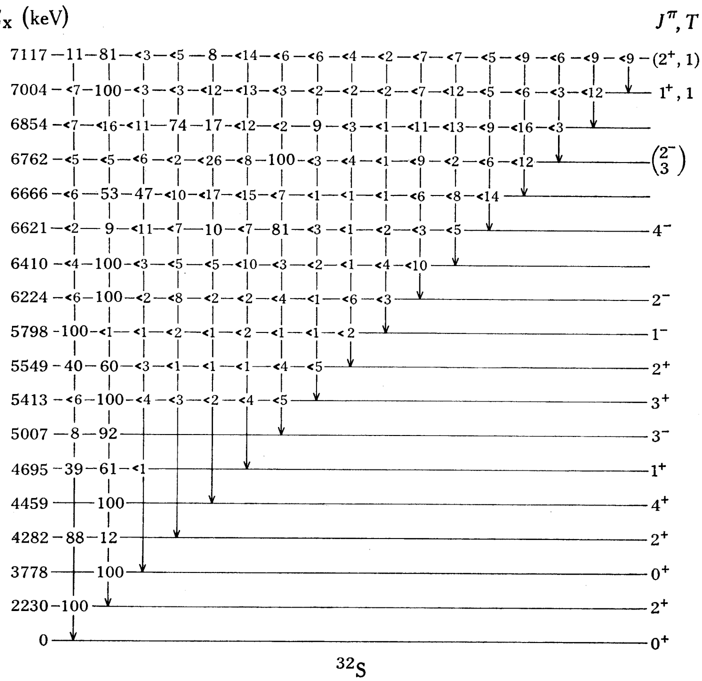


Fig. 2.—Gamma ray branching ratios of ^{32}S levels. The branching ratios for levels above $E_x = 5 \cdot 1$ MeV are from the present work. The branching ratios of levels below $5 \cdot 1$ MeV, as well as all of the spins, parities, and excitation energies, are as listed by Coetzee *et al.* (1972). The parentheses for the J^π, T assignments to the 6762 and 7117 keV levels indicate that these assignments are not as well established as the others.

The branching ratios obtained are summarized in Table 1, and upper limits for unobserved transitions are shown in Figure 2. The errors indicated in Table 1 are due to statistical uncertainties in the data and to uncertainties inherent in the line-shape analysis. No attempt has been made to correct for errors arising from anisotropies in the γ-ray angular distributions. For a 2 MeV γ-ray, the attenuation factors for the geometry used are $Q_2 = 0{\cdot}56$ and $Q_4 = 0{\cdot}06$, and therefore the effects of anisotropies are considerably reduced; Elliott *et al.* (1968*b*) have estimated 15% as a safe upper limit on the consequent error in γ-ray intensities.

TABLE 1

GAMMA RAY BRANCHING RATIOS IN ^{32}S

Initial state E_x† (keV)	Final state E_x† (keV)	Branching ratios* (%) Present work	C	F	VF	P	EV
5413	0	<6	<10			<1	4
	2230	100	90±5	100	100	100	96
	3778	<4	<20				
	4282	<3	<10				
	Unknown		10				
5549	0	40±2	41±5	40±10	45	22	45
	2230	60±2	59±5	60±10	55	78	55
5798	0	100	100	100	100		100
	2230	<1	<5				
6224	0	<6	<2			<0·5	<1
	2230	100	100	100		100	100
6410	0	<4					
	2230	100		100			100
6621	2230	9±3	3±2			2	10
	4459	10±3	28±5	15±10		24	
	5007	81±5	66±5	85±10		73	90
	5413	<3	(3±2)				
6666	0	<6	<6				
	2230	53±5	(50)			51	
	3778	47±5	(50)			49	
6762	0	<5	3±2				
	2230	<5	<25				
	5007	100	(97)				
6854	0	<7	<10				
	2230	<16	<20				
	4282	74±8	100	70±10			
	4459	17±7		20±10			
	5413	9±6		10±5			
7004	0	<7	<1		25		
	2230	100	90±5	100	75		
	3778	<3	<10				
	4282	<3	<8				
	Unknown		10				
7117	0	11±3	4±3				
	2230	81±4	92±5				
	3778	<3	<5				
	4282	<5	4±3				
	4459	8±4					

* References to other results are: C, Coetzee *et al.* (1972); F, Forsblom *et al.* (1970); VF, Viitasalo and Fant (1970); P, Piluso *et al.* (1969); EV, Endt and Van der Leun (1967).

† The excitation energies are taken from Coetzee *et al.* (1972).

IV. Discussion

The branching ratios obtained are compared with previous results in Table 1. The present results for the 5798 and 6224 keV levels are in good agreement with previous work and do not require further discussion.

5413 keV Level

This level has spin and parity 3^+ (Ollerhead *et al.* 1970). The present data are consistent with a 100% branch to the 2230 keV 2^+ level. Coetzee *et al.* (1972) indicate that this transition accounts for only $(90 \pm 5)\%$ of the decay of the level and that therefore $(10 \pm 5)\%$ of the decay must consist of transitions to other levels. The present limits, combined with the limit of 1% set by Piluso *et al.* (1969) for a ground-state branch, are just consistent with this.

5549 keV Level

The decay scheme obtained for this level agrees with all previous measurements except those of Piluso *et al.* (1969).

6410 keV Level

The present results agree with both previous results. The spin and parity of the level are not known; if it is assumed that the 100% transition to the 2230 keV 2^+ state has as its lowest order multipole either E1, M1, or E2, then it follows that $J^\pi = 0^+, 1^\pm, 2^\pm, 3^\pm$, or 4^+. This level is a good candidate either for the second 4^+ level predicted by Wildenthal *et al.* (1971) at $E_x = 5 \cdot 6$ MeV or for the 3^- member of the quintuplet expected from the quadrupole–octupole vibrational model (Mermaz *et al.* 1969; Gardner *et al.* 1972).

6621 keV Level

This level has a spin and parity of 4^- (Dorum 1968; Cairns *et al.* 1972; Coetzee *et al.* 1972). There is considerable disagreement among the various measurements of the branching ratios. Coetzee *et al.* report a tentative new branch of $(3 \pm 2)\%$ to the 5413 keV 3^+ level, and the limit reported here ($< 3\%$) is not inconsistent with this. The level was found to be strongly resonant at a bombarding energy of $8 \cdot 97$ MeV.

6666 keV Level

All measurements agree that this level decays with approximately equal probability to the 2230 keV 2^+ state and the 3778 keV 0^+ state. The spin and parity of the level are not known, but if it is assumed that for each of the two decay modes the lowest order multipole is either E1, M1, or E2, then the decay scheme requires that $J^\pi = 1^\pm$ or 2^+. It is remarkable that there is no evidence for a ground-state transition even though there is a strong branch to the 3778 keV 0^+ level.

6762 keV Level

Coetzee *et al.* (1972) report a $(3 \pm 2)\%$ branch to the ground state, based upon observation at one of the two $^{31}P(p,\gamma)^{32}S$ resonances at which they found the level to be populated. They tentatively concluded that the remainder of the decay consisted of a 97% branch to the 5007 keV 3^- level. The present results indicate a 100% branch to the 5007 keV level, but the upper limit of 5% for a ground-state branch is not inconsistent with the results of Coetzee *et al.* These authors argued that the level has a spin and parity of 2^- or $3^{\pm}$, based largely on their observation of a ground-state branch. Confirmation of this branch is desirable. If no such branch exists, the decay scheme of the level is very distinctive (i.e. 100% to the 5007 keV 3^- level) and is suggestive of a strong generic relationship between the two levels.

6854 keV Level

The spin and parity of this level are not known. The present results confirm the branches to the 4459 keV 4^+ level and the 5413 keV 3^+ level which were reported by Forsblom *et al.* (1970) but not by Coetzee *et al.* (1972). If it is assumed that for each of the three decay modes the lowest order multipole is either E1, M1, or E2, then the decay scheme requires $J^{\pi} = 2^+, 3^{\pm}$, or 4^+.

7004 keV Level

This level is believed to be the first $J^{\pi} = 1^+$, $T = 1$ state (Armini *et al.* 1968; Maripuu and Wildenthal 1972). The major decay is to the 2230 keV 2^+ state. There is no evidence in the present work for the 25% ground-state branch reported by Viitasalo and Fant (1970). The present results are not inconsistent with a total intensity of $(10 \pm 5)\%$ to levels other than the 2230 keV level (Coetzee *et al.* 1972). Maripuu and Wildenthal (1972) have performed shell-model calculations of $\Delta T = 1$, M1 transition strengths in ^{32}S. Assuming pure M1 transitions, they calculate branches of 12% and 88% to the ground state and 2230 keV state respectively.

7117 keV Level

Graue *et al.* (1968) have made a tentative assignment of $J^{\pi} = 2^+$, $T = 1$ to this level. The decay scheme obtained in the present work disagrees with that reported by Coetzee *et al.* (1972).

V. Conclusions

By means of a particle–gamma coincidence study of the reaction $^{32}S(p, p'\gamma)^{32}S$, the decay schemes for all known levels in ^{32}S between $E_x = 5 \cdot 40$ and $7 \cdot 15$ MeV have been determined. The results verify some previous work and provide additional evidence concerning controversial branching ratios. Most of the previous information has been obtained from study of the reaction $^{31}P(p, \gamma)^{32}S$ with Ge(Li) detectors and, since the resulting spectra are usually complex, ambiguities sometimes occur and it is not always easy to assign useful upper limits to unobserved branches. However, the technique used here is highly selective in that each spectrum contains only those γ-rays associated with the decay scheme of the level being studied. Thus, in spite of the inferior resolution of the NaI(Tl) detector, ambiguities rarely arise and upper limits on the relative intensities of unobserved branches may be readily assigned.

In this energy range in ^{32}S the most pressing problem now is the determination of the spins and parities of the 6410, 6666, 6762, 6854, and 7117 keV levels. This knowledge is essential before worthwhile comparisons with the various nuclear models can be made.

VI. Acknowledgments

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