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Electromagnetic properties of the 6621- and 7950-keV levels in ^{32}S

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Lifetime and γ-ray angular distribution measurements have been carried out at the 1247-, 1399-, 1402-, 1437-, and 1581-keV resonances of the $^{31}P(p,\gamma)^{32}S$ reaction. Mean lifetime values have been measured for the 5006-, 5413-, 6224-, 6621-, and 7950-keV levels. The J^π value of the 7950-keV level has been determined as $J^\pi = 4^-$. The strengths of some isoscalar $M2$ transitions were measured. Electromagnetic features of the 6621-keV level are discussed in the framework of the vibrational model.

[NUCLEAR REACTIONS $^{31}P(p,\gamma)$, $E=1.25$–1.58 MeV; measured $I_\gamma(\theta)$, Doppler-shift attenuation. ^{32}S deduced levels, γ branching, mixing ratios, J, π, τ_m.]

I. INTRODUCTION

In the framework of the vibrational model, it was suggested by Gardner *et al.*[1] that some odd-parity ^{32}S levels could result from the coupling of the one-phonon quadrupole state ($E_x = 2230$ keV, $J^\pi = 2^+$) with the one-phonon octupole state ($E_x = 5006$ keV, $J^\pi = 3^-$). A quintuplet of odd-parity states, $J^\pi = (1-5)^-$ would result from such a coupling and the γ decay of the quintuplet members would exhibit an $E2$ transition to the one-phonon octupole state and an $E3$ transition to the one-phonon quadrupole state. The strengths of these transitions should be comparable to the strengths of the $2230 \rightarrow 0$ and $5006 \rightarrow 0$ transitions. Gardner *et al.*[1] identified tentatively the $E_x = 5798$-, 6224-, and 6621-keV levels ($J^\pi = 1^-$, 2^-, and 4^-, respectively) with the 1^-, 2^-, and 4^- members of such a quintuplet, and studied the electromagnetic decay of the first of these levels.

The first aim of this work was to obtain, in the electromagnetic decay of the $E_x = 6224$- and 6621-keV levels, information to be compared with the predictions of the model. The $E_x = 6621$-keV level which decays[2] to the $E_x = 2230$- and 5006-keV level is of particular interest. The $6621 \rightarrow 5006$ transition is essentially $E2$[3,4] in agreement with the predictions of the model. However, the mixing ratio $\delta(E3/M2)$ of the $6621 \rightarrow 2230$ transition has never been measured prior to the present work. Due to the importance of the $E_x = 5006$-keV level in the model, its electromagnetic properties were also reinvestigated.

Another aim was to study the $6621 \rightarrow 4459$ keV, $4^- \rightarrow 4^+$ transition. A previous study[3] yielded a value of the mixing ratio $\delta(M2/E1) = 0.23 \pm 0.03$; using the available information[2] about the lifetime and the branching ratio, this δ value led to a $\Delta T = 0$, $M2$ strength of 3.3 ± 1.1 W.u. (Weisskopf units), which is much higher than the upper limit of 0.1 W.u. given[5] to such isoscalar $M2$ transitions.

Information necessary to reach both aims was obtained through electromagnetic decay spectra, γ-ray angular distribution measurements, and lifetime measurements using the Doppler shift attentuation method (DSAM). These measurements were carried out at strong resonances of the $^{31}P(p,\gamma)^{32}S$ reaction which feed[3] the levels at $E_x = 5006$ keV ($E_p = 1247$ and 1402 keV), $E_x = 6224$ keV ($E_p = 1247$ keV), and $E_x = 6621$ keV ($E_p = 1437$ and 1581 keV).

II. EXPERIMENTAL ARRANGEMENT

Red phosphorus targets (40, 60, and 90 $\mu g/cm^2$) were prepared by evaporation in vacuum[6] on a carefully cleaned 0.2 mm thick gold backing and bombarded by the proton beam from the 3-MV Van de Graaff accelerator of the Centre de Recherches Nucléaires of Strasbourg-Cronenbourg. Targets were placed at 45° with respect to the direction of the beam in an air-cooled target holder. Before hitting the target, the beam passed through a liquid nitrogen trap which reduced considerably carbon buildup on the target during the measurements.

γ rays were detected using Ge(Li) detectors. A 49 cm^3 detector located at a distance of 9 cm from the target was used at the 1247- and 1402-keV resonances, and another one (69 cm^3) located at a distance of 8 cm from the target was used at the 1437- and 1581-keV resonances. The resolution of both detectors was 3 keV full width at half-maximum (FWHM) at 1.33 MeV (^{60}Co). Each of these detectors was mounted on an arm rotating around the impact point of the beam on the target. During the angular distribution measurements, another Ge(Li) detector located at 90° with respect to the direction of the beam was used as a monitor. The anisotropy of the arrangement was checked by measuring in the same experimental conditions the isotropic angular distribution of the 844 keV γ ray emitted at the 1683-keV resonance of the ^{27}Al-$(p,p_1'\gamma)^{27}$Al reaction.[7]

Attenuation coefficients resulting from the finite size of the detectors were calculated[8] for the distances quoted above. These coefficients are $Q_2 = 0.96$, $Q_4 = 0.86$, and $Q_6 = 0.72$ for the 69 cm^3 detector and $Q_2 = 0.97$, $Q_4 = 0.91$, and $Q_6 = 0.82$ for the 49 cm^3 detector.

The efficiency curve for each of the detectors was obtained with an accuracy of about 10% using a ^{56}Co source (for $E_\gamma < 3.2$ MeV) and transitions with known intensity[9] emitted at the 992-keV resonance of the ^{27}Al$(p,\gamma)^{28}$Si reaction (for $E_\gamma > 3.2$ MeV). The efficiency curves were also computed using a Monte Carlo procedure.[10] The agreement between these two determinations is good.

III. BRANCHING RATIOS OF BOUND STATES

The resonance energy values from Ref. 3 and the excitation energy values from Ref. 4 (except when a more accurate value is obtained from the present work) are used throughout this paper.

At the four resonances 1247-, 1402-, 1437-, and 1581-keV, γ-ray spectra were taken at five angles ($\theta = 0°$, 30°, 45°, 60°, and 90°). A typical spectrum at the 1437 keV resonance is presented in Fig. 1. Due to the target thickness, transitions from the two neighboring resonances at 1399 and 1402 keV were observed in the same spectra. In order to achieve a statistical accuracy better than 10% for the peak area corresponding to the 6621 → 2230 transition, a charge of 90 mC was necessary for each measurement at the 1437- and 1581-keV resonances. A charge of 50 mC was accumulated for the measurements at the other resonances. Angular distribution measurements were accounted for in deducing γ-decay schemes from γ-ray spectra: for the resonance levels these decay schemes (Table I) are in excellent agreement with previous results.[3] Branching ratios from the present work are presented in Table II for some bound states; except for the 6224 → 5006 transition which will be

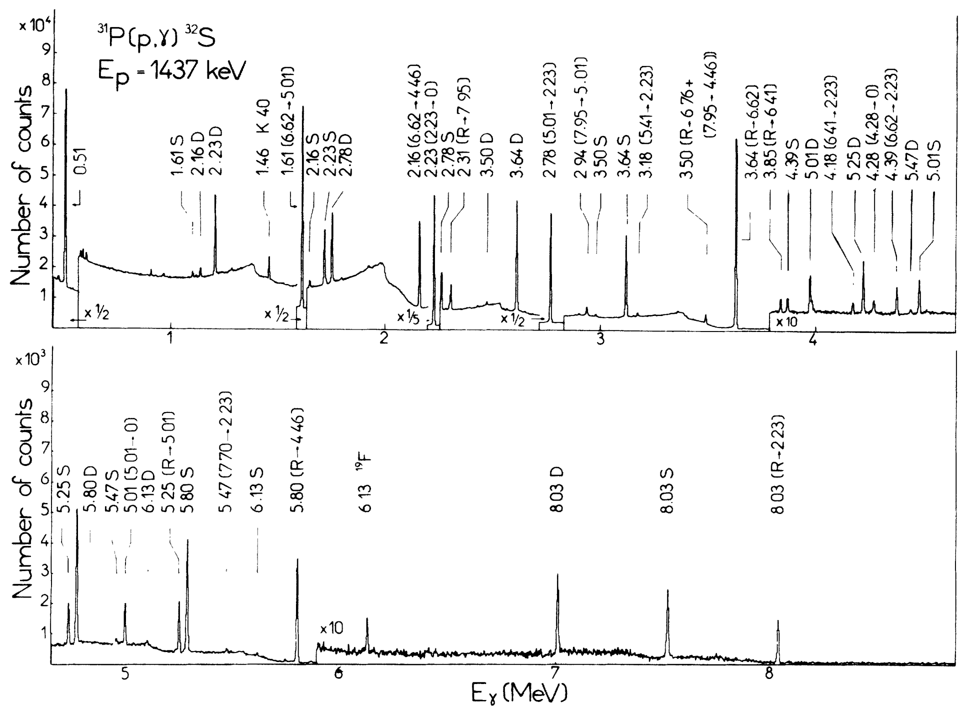

FIG. 1. Sum of the two γ spectra taken at 45° during the angular distribution measurements at the 1437-keV resonance. The Ge(Li) detector (69 cm^3) was located at a distance of 8 cm from the target. The total charge collected was 180 mC. The 6.13-MeV γ ray is due to the contaminant reaction ^{19}F$(p,\alpha\gamma)^{16}$O. The letters S and D stand for single and double escape peaks, respectively.

TABLE I. Branching ratios (%) of the resonance levels. The accuracy is about 10% for the primaries with an intensity larger than 10%; for the others it stands between 20 and 40%.

E_p [a] (MeV)	E_x [a] (MeV)	E_f (MeV) $J^\pi_{x_i} \diagdown J^\pi_f$	0 0^+	2.23 2^+	4.28 2^+	4.46 4^+	4.70 1^+	5.01 3^-	5.41 3^+	6.22 2^-	6.41 4^+ [b]	6.62 4^-	6.76 $(3^-, 4^+, 5^-)$	Other levels
1.247	10.072	2^-	1.8	28	1.6		0.9	12	4	50				7.11(0.7), 8.13(0.3), 8.30(0.4), 8.50(0.2)
1.402	10.222	3^-		12		22		66						
1.437	10.256	4^-		0.5	<0.1	8		4	<0.1		0.5	77	4.1	6.85(<0.8), 7.35(<1), 7.70(<0.5), 7.95(6.2)
1.581	10.395	4^-		0.3	<0.1	1.1		5.6	<0.2		0.5	84	2.7	6.85(1.3), 7.70(0.7), 7.95(4.2)

[a] References 2 and 3.
[b] Reference 23 (see Sec. VI A).

discussed in Sec. III B, the accuracy of the branching ratios is better than 15%. This accuracy is achieved for each transition by adding quadratically the statistical error and a 10% error in the efficiency curve. Our results are in good agreement with those of Ref. 2 and those recently obtained[4,11] in studies of the $^{31}P(p,\gamma)^{32}S$ reaction.

From γ-ray spectra taken at 90° during the lifetime measurements, accurate values for the excitation energy of the 5006-, 6621-, and 7950-keV levels were deduced (Table II, column 1) and are in excellent agreement with Ref. 12. Some results from Table II are discussed below.

A. E_x =5006-keV level

The branching ratios were measured at the 1437-keV resonance which feeds the 5006-keV level both directly and through the 6621-keV level.

B. E_x =6224-keV level

The weak 6224 → 5006 transition previously reported[4] at the 895-keV resonance was observed in the present work at the 1247-keV resonance with a relative intensity of (3 ± 2)%. Due to the difficulty of resolving this weak transition (E_γ = 1218 keV) from the intense double escape peak of the 2230 → 0 keV one (E_γ = 1208 keV), the branching ratio is determined with an accuracy of only 60%. The existence of this transition was predicted in the framework of the quadrupole-octupole coupling model quoted in Sec. I.

C. E_x =6621-keV level

The branching ratios of the transitions to the 2230-, 4459-, and 5006-keV levels are in very good agreement with other determinations.[4,11,13]

As in previous works,[4,12] the feeding of the 5413-keV level by the 6621-keV level was deduced from the observation of a 3183-keV γ ray, which corresponds to the 5413 → 2230 transition. The intensity of this transition, observed at the two resonances at 1437 and 1581 keV, cannot be accounted for by the direct feeding of the 5413-keV level by the resonance levels (Table I). The 6621 → 5413 transition cannot be separated from the double

TABLE II. γ-ray branching ratios of some bound levels of ^{32}S.

E_{xi} [a] (keV) \ E_{xf} (keV)	0	2230	4459	5006	5413	Unknown
5006.2 ±0.3	3.4 ± 0.4	96.6 ± 0.4				
6224.3 ±0.9	<0.5	97 ± 2		3 ± 2		
6621.1 ±0.3		1.7 ± 0.3	22 ± 3	75 ± 3	(1.4 ± 0.2) [b]	
6761.7 ±0.3	<1		35 ± 10 [c]			65 ± 10
7950.0 ±0.4			<15	65 ± 7		35 ± 7

[a] Excitation energies of the 5006-, 6621-, and 7950-keV levels are from this work; excitation energies of the 6224- and 6762-keV levels are from Ref. 2.
[b] Parentheses mean that the transition was not observed directly (see text Secs. III C and III D).
[c] Only this transition was observed.

escape peak of the 2230 → 0 transition in the γ-ray spectra.

D. E_x =6762-keV level

We observed only one decay branch (6762 → 4459) which accounts for about 35% of the intensity of the primary transition r → 6762. The strong transition (6762 → 5006) which was seen in a study[14] of the $^{32}S(p, p'\gamma)^{32}S$ reaction cannot be separated in our γ-ray spectra from the double escape peak of the 5006 → 2230 transition. From the present work an upper limit of 1% is given to the 6762 → 0 transition, whereas in Ref. 12 an intensity of (3 ± 2)% is quoted.

E. E_x =7950-keV level

The 7950 → 5006 transition accounts for only 65% of the intensity of the primary radiation. A 7950 → 4459 transition has been previously observed in γ -ray spectra taken at the 1437-keV resonance (for instance in Refs. 4 and 13). But Coetzee, Meyer, and Reitmann[12] noticed that this transition (if it exists) could be confused with the primary radiation feeding the 6762-keV level. From the spectra taken at the 1581 keV resonance we give an upper limit of 15% of the intensity of the r → 7950 transition to the intensity of the 7950 → 4459 transition, which can be compared to the upper limit of 6% derived by Coetzee *et al.*[12] Due to the possible existence of this transition, the results of the angular distribution measurements of the primary transition feeding the 6762-keV level at the 1437-keV resonance were not taken into account.

IV. ANGULAR DISTRIBUTION ANALYSIS

Angular distribution measurements of very weak transitions [r → 6410 keV (0.5%) and 6410 → 2230 keV at the 1437-keV resonance; r → 6852 keV (1.3%) and 6852 → 4282 keV at the 1581-keV resonance] were possible because the charge collected was large. Legendre polynomial coefficients A_2 and A_4 and multipole mixing ratios δ resulting from a least-squares analysis of the measured angular distributions are presented in Table III. Using a computer code, which has been previously described,[3] one calculates the function

$$Q^2=\sum_i\{[N_{i_{\rm exp}}-N_{i_{\rm th}}(P_0,\delta)]/\Delta N_{i_{\rm exp}}\}^2\,,$$

where $N_{i_{\rm exp}}$ is the experimental value, $N_{i_{\rm th}}$ is the theoretical one calculated with the formalism and the phase convention of Rose and Brink,[15] $\Delta N_{i_{\rm exp}}$ is the experimental error, and P_0 is the population parameter of the $m=0$ magnetic substate. The sum is taken over the five angles. A solution δ was accepted if it yielded a minimum for the Q^2 function below the 0.1% confidence limit. The spin values from Refs. 2 and 3 were used in the analysis. The value $P_0 = 0.41 \pm 0.02$ obtained at the 1247-keV resonance from the angular distribution analysis of the pure $M2$ r → 0 transition is in good agreement with the determination of Ref. 3 ($P_0 = 0.42 \pm 0.02$). For the other resonances, the P_0 values of Ref. 3 were used throughout the analysis: $P_0 = 0.43$ (E_p = 1399 keV), 0.38 (E_p = 1402 keV), 0.44 (E_p = 1437 and 1581 keV).

The data for and analysis of the angular distributions of the transitions from the 6621-keV level are presented as examples in Fig. 2. These transitions are of particular interest in the present work. The spins of the 6410-, 6852-, and

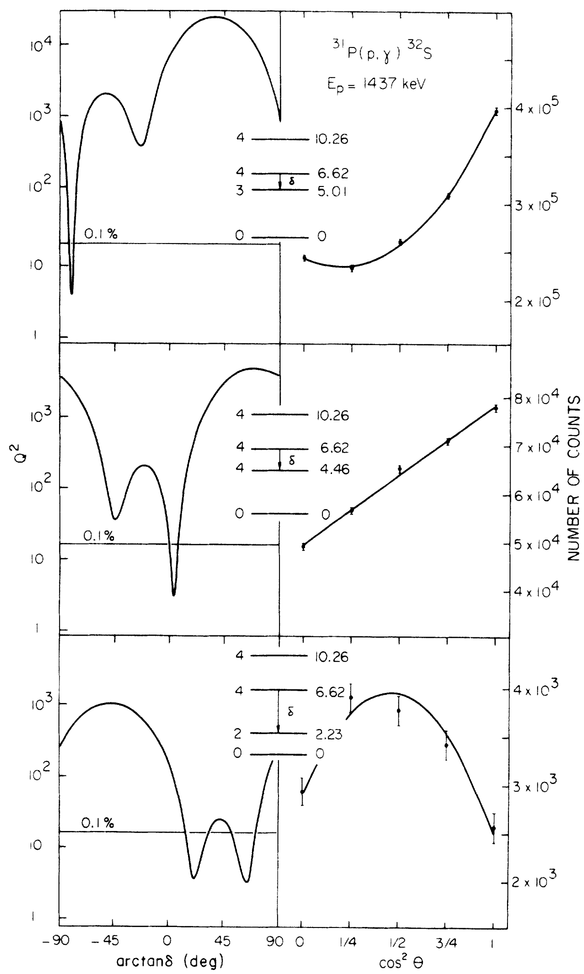

FIG. 2. γ-ray angular distributions of the 6.62 → 5.01, 6.62 → 4.46, and 6.62 → 2.23 MeV transitions are shown on the right-hand part of the figure. Lines are theoretical curves calculated with the values of δ resulting from the analysis (Table III) and the value P_0 = 0.44. The results of the analysis are shown on the left-hand part of the figure.

TABLE III. Measured angular distributions of γ rays deexciting ^{32}S levels: Legendre polynomial coefficients and mixing ratios.

E_p (keV)	$E_{x_i} \to E_{x_f}$ (MeV)	A_2	A_4	$J_i^\pi \to J_f^\pi$ [a]	Mixing ratio
1247	10.07 → 0	0.43 ± 0.01	−0.02 ± 0.01	$2^- \to 0^+$	
	10.07 → 2.23	0.36 ± 0.02	−0.01 ± 0.02	$2^- \to 2^+$	−0.02 ± 0.03
	10.07 → 4.28	0.29 ± 0.08	0.01 ± 0.08	$2^- \to 2^+$	0.05 ± 0.09
	10.07 → 5.01	−0.03 ± 0.01	0.00 ± 0.01	$2^- \to 3^-$	0.06 ± 0.01
	10.07 → 5.41	−0.11 ± 0.02	0.03 ± 0.02	$2^- \to 3^+$	0.00 ± 0.03
	10.07 → 6.22	0.33 ± 0.03	0.00 ± 0.03	$2^- \to 2^-$	0.02 ± 0.03
	6.22 → 2.23	0.14 ± 0.01	−0.01 ± 0.01	$2^- \to 2^+$	0.07 ± 0.03 [b]
	5.41 → 2.23	−0.12 ± 0.06	0.07 ± 0.07	$3^+ \to 2^+$	$\lvert\delta\rvert > 20$
	5.01 → 2.23	−0.23 ± 0.03	−0.02 ± 0.03	$3^- \to 2^+$	0.00 ± 0.03
1399	10.22 → 4.70	0.51 ± 0.07	−0.26 ± 0.09	$3^+ \to 1^+$	−0.02 ± 0.04
	10.22 → 7.12	−0.25 ± 0.01	−0.04 ± 0.01	$3^+ \to 2^+$	−0.04 ± 0.01
	7.12 → 2.23	0.38 ± 0.03	0.02 ± 0.03	$2^+ \to 2^+$	−0.06 ± 0.04 or −1.8 ± 0.3
1402	10.22 → 5.01	0.39 ± 0.01	0.01 ± 0.01	$3^- \to 3^-$	0.02 ± 0.02
	5.01 → 2.23	−0.23 ± 0.01	−0.02 ± 0.01	$3^- \to 2^+$	0.00 ± 0.02
1437	10.26 → 2.23	0.44 ± 0.02	−0.25 ± 0.02	$4^- \to 2^+$	0.02 ± 0.01
	10.26 → 4.46	0.46 ± 0.01	−0.03 ± 0.01	$4^- \to 4^+$	−0.03 ± 0.04
	10.26 → 5.01	−0.52 ± 0.02	0.00 ± 0.02	$4^- \to 3^-$	0.11 ± 0.02
	10.26 → 6.41	0.55 ± 0.03	0.00 ± 0.04	$4^- \to 3^-$ $4^- \to 4^+$	−0.50 ± 0.08 −0.24 ± 0.18
	10.26 → 6.62	0.46 ± 0.01	−0.02 ± 0.01	$4^- \to 4^-$	−0.02 ± 0.04
	10.26 → 6.76	−0.25 ± 0.03	0.01 ± 0.03		[c]
	10.26 → 7.95	0.31 ± 0.01	−0.03 ± 0.01	$4^- \to 4^-$	0.18 ± 0.02
	7.95 → 5.01	−0.15 ± 0.02	0.18 ± 0.02	$4^- \to 3^-$	7.9 ± 1.5
	6.62 → 2.23	0.05 ± 0.05	−0.30 ± 0.05	$4^- \to 2^+$	0.41 ± 0.08 or 2.1 ± 0.4
	6.62 → 4.46	0.35 ± 0.01	−0.03 ± 0.01	$4^- \to 4^+$	0.06 ± 0.02
	6.62 → 5.01	0.32 ± 0.01	0.21 ± 0.01	$4^- \to 3^-$	−5.5 ± 0.3
	6.41 → 2.23	0.17 ± 0.09	−0.15 ± 0.09	$3^- \to 2^+$ $4^+ \to 2^+$	−0.28 ± 0.14 0.13 ± 0.11
	5.41 → 2.23	0.32 ± 0.04	0.22 ± 0.04	$3^+ \to 2^+$	[d]
1581	10.40 → 2.23	0.36 ± 0.05	−0.12 ± 0.05	$4^- \to 2^+$	0.00 ± 0.06
	10.40 → 4.46	0.43 ± 0.03	−0.02 ± 0.03	$4^- \to 4^+$	0.02 ± 0.06
	10.40 → 5.01	0.06 ± 0.01	−0.03 ± 0.01	$4^- \to 3^-$	−0.19 ± 0.02
	10.40 → 6.62	0.41 ± 0.01	−0.01 ± 0.01	$4^- \to 4^-$	0.05 ± 0.03
	10.40 → 6.76	−0.07 ± 0.05	0.01 ± 0.06	$4^- \to 3^-$ $4^- \to 4^+$ $4^- \to 5^-$	−0.13 ± 0.04 0.55 ± 0.11 0.07 ± 0.05
	10.40 → 6.85	0.57 ± 0.09	−0.03 ± 0.10	$4^- \to 3^-$ $4^- \to 4^+$	−0.50 ± 0.15 −0.3 ± 0.3
	10.40 → 7.95	0.41 ± 0.06	−0.02 ± 0.07	$4^- \to 4^-$	0.05 ± 0.11
	7.95 → 5.01	−0.13 ± 0.08	0.29 ± 0.09	$4^- \to 3^-$	11 ± 2
	6.85 → 4.28	0.48 ± 0.04	−0.10 ± 0.04	$3^- \to 2^+$ $4^+ \to 2^+$	−0.50 ± 0.12 −0.09 ± 0.09
	6.76 → 4.46	−0.04 ± 0.02	−0.03 ± 0.03	$3^- \to 4^+$ $4^+ \to 4^+$ $5^- \to 4^+$	0.05 ± 0.04 0.60 ± 0.08 −0.12 ± 0.03
	6.62 → 2.23	0.02 ± 0.03	−0.28 ± 0.03	$4^- \to 2^+$	0.41 ± 0.08 or 2.1 ± 0.3
	6.62 → 4.46	0.35 ± 0.02	−0.02 ± 0.02	$4^- \to 4^+$	0.05 ± 0.02
	6.62 → 5.01	0.31 ± 0.01	0.22 ± 0.01	$4^- \to 3^-$	−5.5 ± 0.4
	5.41 → 2.23	0.17 ± 0.05	0.12 ± 0.06	$3^+ \to 2^+$	[d]

[a] The J^π values are from Refs. 2 and 3, and from this work.

[b] See also Sec. VI C.

[c] The angular distribution of this transition was not analyzed at this resonance (see Sec. III E).

[d] The angular distribution of the last member of the 10.40 → 6.62 → 5.41 → 2.23 cascade was analyzed to obtain the mixing ratio of the 6.62 → 5.41 unobserved transition (see Sec. III C). Using the values δ(5.41 → 2.23) obtained at the 1247-keV resonance and $\delta(r \to 6.62)$, the value δ(6.62 → 5.41) = 0.0 ± 0.5 was obtained.

7950-keV levels will be discussed in Sec. VI. The present values for mixing ratios are in agreement with previously published results[2,3] for most of the transitions. A disagreement with our previous work[3] must be pointed out: the value of the mixing ratio $\delta(M2/E1)$ of the 6621→4459 transition from this work ($\delta = 0.06 \pm 0.02$) is markedly different from the one of Ref. 3) ($\delta = 0.23 \pm 0.03$). The new $M2$ transition strength value will be discussed in Sec. VI.

V. MEAN LIFETIME DETERMINATIONS

Lifetimes presented in Table IV were obtained at various resonances using the Doppler-shift attenuation method. Target thicknesses (60 and 90 $\mu g/cm^2$) and incident proton energies were adjusted so as to ensure that the recoiling sulfur ions stop in the phosphorus layer. At the 1402-, 1437-, and 1581-keV resonances, the lifetimes were deduced from γ-ray spectra taken at $\theta = 0°$, 90°, and 130°; dispersions were 220 eV/channel for the determination of the 6621-keV level lifetime, 370 eV/channel (5006-keV level) and 930 eV/channel (7950-keV level). At the 1247-keV resonance lifetimes were deduced from the data taken at six angles, a measurement at 130° being included in a set of angular distribution measurements. The dispersion was 700 eV/channel. Two sets of measurements were carried out at the 1247-, 1437-, and 1581-keV resonances, and four sets at the 1402-keV one. Lines from radioactive sources (^{56}Co at the 1437- and 1581-keV resonances; ^{208}Tl and ^{24}Na at the others) were simultaneously stored in the spectra as a check on possible drifts in electronics.

The finite size of the detectors was accounted for by calculating[16] a mean value for the observation angle:

$$\langle\cos\theta\rangle = \sum_l \{A_l[(l+1)Q_{l+1}P_{l+1}(\cos\theta) + lQ_{l-1}P_{l-1}(\cos\theta)]/(2l+1)\} \Big/ \sum_l A_l Q_l P_l(\cos\theta)\,,$$

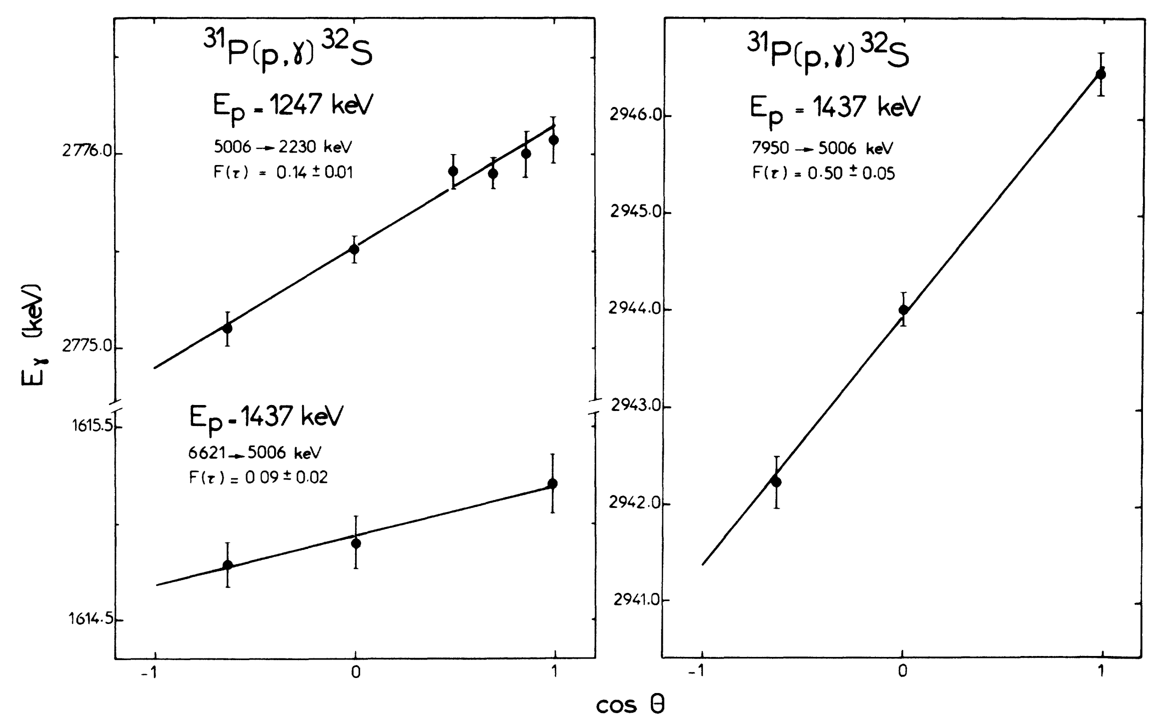

FIG. 3. Variation of the energy of some transitions with $\cos\theta$. Experimental data are from one set of measurements, and lines result from a least-squares fit to the experimental data. The indicated $F(\tau)$ values and errors are the mean values presented in Table IV.

TABLE IV. Doppler shifts and mean lives of some ^{32}S bound states.

E_x (keV)	Transition (MeV)	Proton energy (keV)	$F(\tau_m)$	τ_m [a] (fs)
5006	$5.01 \rightarrow 2.23$	1247	0.14 ± 0.01	580^{+60}_{-40}
		1402	0.14 ± 0.02	620^{+190}_{-90}
5413	$5.41 \rightarrow 2.23$	1247	0.39 ± 0.04	160 ± 30
6224	$6.22 \rightarrow 2.23$	1247	0.60 ± 0.02	75 ± 10
6621	$6.62 \rightarrow 5.01$	1437	0.09 ± 0.02	1000^{+350}_{-200}
		1581	0.10 ± 0.02	950^{+350}_{-200}
7950	$7.95 \rightarrow 5.01$	1437	0.50 ± 0.05	115 ± 20
		1581	0.45 ± 0.05	145 ± 20

[a] Indicated uncertainties are statistical errors only. The final adopted values are given in column 2 of Table V.

where A_l are the Legendre polynomial coefficients of the measured angular distribution, and Q_l are the attenuation coefficients of the detector. For each set of measurements, the Doppler-shift attenuation factor $F(\tau_m)$ which is defined as the ratio of the observed to the full Doppler shift was obtained using a least-squares fit to the data from the expression

$$E_\gamma(\theta) = E_\gamma(90°)[1 + F(\tau_m)(v_R/c)\langle\cos\theta\rangle],$$

where v_R is the recoiling nucleus velocity. Some examples of such an analysis are shown in Fig. 3. Mean values of $F(\tau_m)$ obtained at each resonance from each set of measurements are presented in the fourth column of Table IV. All primary transitions exhibit full Doppler shifts within 3%. Mean lifetimes τ_m (Table IV, column 5) are derived from the observed $F(\tau_m)$ by means of a computer program based on Blaugrund's calculations.[17] The corrections by Ormrod, McDonald, and Duckworth[18] on the electronic stopping cross section were included in the calculation.

Adopted values for τ_m are compared with some recent values[2,4,19,20] in Table V. Each quoted error is derived by adding quadratically the experimental error and an estimated error of 15% for insufficient knowledge of the slowing down of the recoiling ions in the target material.

Transition strengths presented in Table VI are derived from mean lifetimes and mixing ratios measured in the present work. The quoted errors are obtained by adding quadratically errors on mean lifetimes, branching and mixing ratios.

VI. DISCUSSION

A. E_x =6410- and 6852-keV levels

Natural parity was assigned to the 6410- and 6852-keV levels in recent studies at 180° of the $^{32}S(\alpha,\alpha')^{32}S$ reaction.[4,21] So the J^π values from Ref. 3 [$(2^-, 3^\pm, 4^+)$ and $(3^\pm, 4^+)$ for the 6410- and 6852-keV levels, respectively] are limited to 3^- and 4^+ and the analysis of the angular distribution data were carried out for these two J^π values

TABLE V. Comparison of mean lifetime values obtained in various experiments.

E_x (keV)	Mean lifetimes (fs) This work [a]	Ref. 2	b	c	d
5006	600 ± 140	600 ± 100		1550 ± 380	795 ± 130
5413	160 ± 40	125 ± 25			200 ± 40
6224	75 ± 15	80 ± 15			100 ± 17
6621	980 ± 250	390 ± 80	810^{+350}_{-250}	560 ± 110	1520 ± 310
7950	130 ± 25		110^{+60}_{-40}		

[a] A 15% error was quadratically added to the statistical error to account for the insufficient knowledge of the slowing down of the ions in the target.
[b] $^{31}P(p,\gamma)^{32}S$ reaction (Ref. 4).
[c] $^{31}P(p,\gamma)^{32}S$ reaction (Ref. 19).
[d] $^{29}Si(\alpha,n)^{32}S$ reaction (Ref. 20).

TABLE VI. Strengths of transitions between some bound states of ^{32}S.

E_{x_i} (MeV)	J_i^π	τ_m (fs)	E_{x_f} (MeV)	J_f^π	Branching ratio (%)	Mixing ratio	Transition strengths (W.u.) $E1$ ($\times 10^4$)	$M1$ ($\times 10^4$)	$E2$	$M2$	$E3$
5.01	3^-	600 ± 140	0	0^+	3.4 ± 0.4	0					20 ± 5
			2.23	2^+	96.6 ± 0.4	0.00 ± 0.02	0.72 ± 0.16			<0.02	
5.41	3^+	160 ± 40	2.23	2^+	100	$\lvert\delta\rvert > 20$		<2	2.5 ± 0.6		
6.22	2^-	75 ± 15	2.23	2^+	97 ± 2	0.07 ± 0.03 [a]	2.0 ± 0.4			$0.27^{+0.29}_{-0.20}$	
6.41	3^-	35 ± 6 [b]	2.23	2^+	100 [c]	-0.28 ± 0.14	3.5 ± 0.7			7.3 ± 5.6	
	4^+					0.13 ± 0.11			3.0 ± 0.5		
6.62	4^-	980 ± 250	2.23	2^+	1.7 ± 0.3	0.41 ± 0.08				0.04 ± 0.01	2.3 ± 1.1
						or				or	or
						2.1 ± 0.4				0.009 ± 0.005	13 ± 4
			4.46	4^+	22 ± 3	0.06 ± 0.02	0.22 ± 0.06			0.07 ± 0.05	
			5.01	3^-	75 ± 3	-5.5 ± 0.3		1.8 ± 0.6	9.0 ± 2.5		
			5.41	3^+	1.4 ± 0.3	0.0 ± 0.5	0.08 ± 0.04			<5	
6.85	3^-	89 ± 20 [d]	4.28	2^+	70 ± 10 [c]	-0.50 ± 0.12	3.6 ± 2.0			60 ± 30	
	4^+					-0.09 ± 0.09			9.2 ± 2.5		
7.95	4^-	130 ± 25	5.01	3^-	65 ± 7	10 ± 3		$1.3^{+1.3}_{-0.6}$	3.0 ± 0.7		

[a] See also text (Sec. VI C).
[b] Reference 20.
[c] Reference 2.
[d] Mean value from Refs. 12 and 22.

(Table III).

The mean value of two lifetime measurements[12,22] of the 6852-keV level is $\tau_m = 89 \pm 20$ fs. With the $J^\pi = 3^-$ assignment an isoscalar $M2$ transition strength of 60 ± 30 W.u. was derived (Table VI) for the $6852 \rightarrow 4282$ transition. This strength is much higher than the 0.1 W.u. upper limit[5] given to the $\Delta T = 0$, $M2$ transitions. However, due to the large error on the derived transition strength, there is a probability of about 5% (assuming a normal distribution for the propagation of the error) that that the real value of the $M2$ strength does not exceed 0.1 W.u. Even though the $J^\pi = 3^-$ value cannot be discarded, $J^\pi = 4^+$ seems, however, more likely to us. Transition strengths derived for both J^π assumptions are presented in Table VI. The $J^\pi = 4^+$ value would lead to an enhanced $E2$ strength (9.2 ± 2.5 W.u.) for the $6852 \rightarrow 4282$ transition.

For the 6410-keV level the $J^\pi = 3^-$ assignment leads to an isoscalar $M2$ transition strength of 7.3 ± 5.6 W.u. (Table VI) for the $6410 \rightarrow 2230$ transition. This $\Delta T = 0$, $M2$ strength is also higher than the 0.1 W.u. upper limit. However, in this case the probability that the real value of the $M2$ strength is less than 0.1 W.u. reaches 20%. Thus, the results of the angular distribution analysis do not allow to us to rule out the $J^\pi = 3^-$ assignment. However, a $J^\pi = 4^+$ value was recently[23] assigned to the 6410-keV level in a study of the $^{34}S(p,t)^{32}S$ reaction. Perhaps this level may be identified with the $E_x = 6.42 \pm 0.05$ MeV, $J^\pi = 4^+$ level which was observed[24] in a study of the $^{32}S(p,p')^{32}S$ reaction at 185 MeV.

B. E_x = 7950-keV level

The analysis of the γ-ray angular distribution measurements carried out at the 1437-keV resonance leads to the unambiguous $J = 4$ value (see Fig. 4). A $J^\pi = 4^+$ assignment must be discarded since a $\Delta T = 0$, $M2$ strength of 100 ± 20 W.u. would be derived for the $7950 \rightarrow 5006$ transition using mean lifetime and mixing ratio values from the present work. Therefore, $J^\pi(7950 \text{ keV}) = 4^-$.

A level for which the $J^\pi = 3^-$ value was proposed[24] has been observed at 7.92 ± 0.07 MeV in a study of the $^{32}S(p,p')^{32}S$ reaction at 185 MeV. This level and the 7950-keV one could be the members of the doublet at 7943 ± 15 keV populated by $l_p = 3$ transfer in the $^{31}P(^3He,d)^{32}S$ reaction.[25]

C. Isoscalar $M2$ transitions

The strengths of these transitions as calculated from our data are presented in Table VI. The special case of the $6852 \rightarrow 4282$ transition has been discussed in Sec. VI A. The high upper limit of the $6621 \rightarrow 5413$ transition results from the large error on the relevant mixing ratio. For the other transitions, the strengths are within the range of the isoscalar $M2$ transition strengths.[5] If the 6224-keV level is the $J^\pi = 2^-$ member of the quintuplet predicted in the quadrupole-octupole coupling model (Sec. I), an $E3$ component should exist in the $6224 \rightarrow 2230$ transition. So the angular distribution analysis of this transition was also carried out including the possibility of a $E3/M2/E1$ mixing. Assuming an $E3$ strength of 20 W.u. (the strength of the $5006 \rightarrow 0$ transition, see Sec. I) one gets

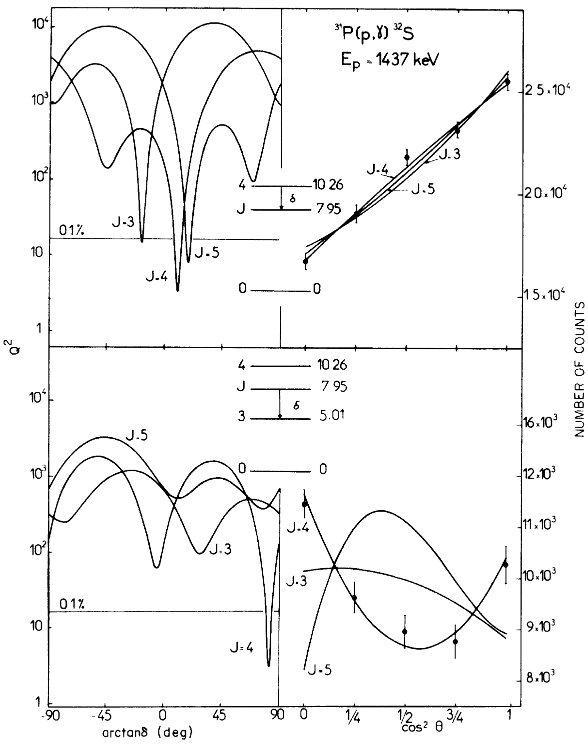

FIG. 4. Upper part: Angular distribution of the $r \rightarrow 7.95$ MeV transition measured at the 1437-keV resonance is shown on the right-hand part of the figure. Lines are theoretical curves calculated with the values of δ resulting from the analysis (Table III) and the value $P_0 = 0.44$. The result of the analysis is shown on the left-hand part of the figure. Lower part: Angular distribution of the $7.95 \rightarrow 5.01$ MeV transition is shown on the right-hand part. Lines are drawn as above. An acceptable solution is obtained only for $J=4$ (left-hand part of the figure).

$\delta(E3/E1) = 0.01 \pm 0.003$ and $\delta(M2/E1) = 0.06 \pm 0.03$. The isoscalar $M2$ strength would then become 0.19 ± 0.18 W.u. We can see that the presence of an $E3$ transition as strong as 20 W.u. would not affect significantly the $E1$ and $M2$ strengths of the 6224-keV level.

D. Vibrational model

The $E2$ strength (9.0 ± 2.5 W.u., Table VI) of the $6621 \rightarrow 5006$ transition is very similar to the $E2$ strength (10.8 ± 1.0 W.u.) of the $2230 \rightarrow 0$ transition calculated with the value $\tau_m = 225 \pm 20$ fs (Ref. 2).

The existence in the $6621 \rightarrow 2230$ transition of the $E3$ strength predicted by the model quoted in Sec. I is established in this work. Unfortunately, it is not possible to select one of the two $\delta(E3/M2)$ values deduced from the analysis of the angular distribution measurements (Table III and Fig. 2). One of them ($\delta = 2.1 \pm 0.4$) leads to an $E3$ strength (13 ± 4 W.u.) which can be compared with the $E3$ strength of the $5006 \rightarrow 0$ transition (20.1 ± 5.1 W.u.) With this δ value the 6621-keV level can be identified with the 4^- member of the quintuplet of levels predicted by the model quoted in Sec. I. However the other value ($\delta = 0.41 \pm 0.08$) yields an $E3$ strength of 2.3 ± 1.1 W.u., conflicting with the predictions of the model. It would be interesting now to do further investigations of the validity of this coupling model by identifying unambiguously other members of the quintuplet. For instance, it is of importance to get information about the $6224 \rightarrow 5006$ and $6762 \rightarrow 5006$ transitions which could not be studied in the present work.

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