Investigation of the Lowest $T = 2$ State of ^{32}S in the $^{31}P + p$ Reactions

J. Vernotte, S. Gales, M. Langevin, and J. M. Maison
Institut de Physique Nucléaire, B. P. n° 1, 91406-Orsay, France
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Two resonances have been observed at 3.283 ± 0.003 and 3.289 ± 0.003 MeV in the $^{31}P(p,\gamma)^{32}S$ reaction. The corresponding excitation energies are 12.044 ± 0.004 and 12.050 ± 0.004 MeV. The γ-decay schemes and resonance strengths have been measured. On the basis of γ-ray angular-distribution and proton elastic scattering measurements the 12.044-MeV level has been assigned $J^\pi,T = 4^-,1$. The 12.050-MeV level has been assigned $J = 0$ from γ-ray angular-distribution and correlation measurements. A proton elastic scattering experiment has yielded an upper limit of 230 eV for the total width of the 12.050-MeV level. This state is shown to be the lowest $J^\pi,T = 0^+,2$ state in ^{32}S.

I. INTRODUCTION

The lowest J^π, $T = 0^+$, 2 state has been observed as a final state in the isospin-allowed (p, t) reaction[1] in many self-conjugate even-even light and medium nuclei. The isospin-forbidden particle decay has also been investigated in the s-d shell (except for ^{36}Ar) through particle-triton coincidence experiments.[2] Therefore it is interesting to look for the possibility of observing these $T = 2$ states as sharp resonances in isospin-forbidden reactions although it may be experimentally difficult to observe an isospin-forbidden resonance among a high density of isospin-allowed resonances.

However, this approach would provide a precise determination of the excitation energy; the γ-decay scheme and the radiative width could be obtained through radiative capture experiments, and information about the total width and the partial width in the entrance channel could be gathered through elastic scattering experiments. It is of special interest to look for possible $\Delta T = 2$ γ transitions which are forbidden in the absence of an isotensor component of the electromagnetic interaction. Such a study was successful for the ^{20}Ne, ^{24}Mg, and ^{28}Si nuclei.[3-7] This study was extended to the ^{32}S nucleus in which the lowest $T = 2$ state had been located at 12.034 ± 0.040 MeV[1] and the main proton isospin-forbidden decay established.[2] It has been pointed out in a preliminary report[8] of the present work that a resonance level observed at 12.050 ± 0.004 MeV in the $^{31}P(p,\gamma)^{32}S$ reaction was a better candidate to be identified with the 12.034 ± 0.040-MeV state than the resonance level at 11.984 ± 0.004 MeV considered in another work.[9]

The purpose of the present paper is to study the properties of the 12.050-MeV state. The γ decay was established and all the energetically allowed but isospin-forbidden particle decays (namely proton and α emission towards the three first levels of ^{31}P and the two first levels of ^{28}Si) were investigated. The spin $J = 0$ of the level was established from angular-distribution and triple-correlation measurements on the main γ-ray cascade from the level. The radiation strengths were obtained from a careful determination of the resonance strength. They are compared with recent theoretical values given by Maripuu and Wildenthal.[10] Finally, an upper limit was deduced for the total width of the state from a proton elastic scattering experiment.

II. EXPERIMENTAL PROCEDURE

The proton beam from the 4-MV Van de Graaf accelerator of the Institut de Physique Nucléaire was momentum analyzed by a 90° magnet calibrated with the $^{13}C(p,n)^{13}N$ reaction threshold at 3.2357 ± 0.0007 MeV.[11]

A. Radiative Capture Experiment

The red-phosphorus target prepared by evaporation in vacuum[12] on a 0.2-mm tungsten backing was 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. Due to the important flux of γ rays from the $^{31}P(p,p'\gamma)^{31}P$ and $^{31}P(p,\alpha_1\gamma)^{28}Si$ reactions the beam intensity was kept to less than 2 μA on a 2-mm-diam spot size. With an electromagnetic wobbling system the targets showed no deterioration after several days of irradiation.

γ rays were detected using 12.7-×12.7-cm NaI(Tl) detectors and a 37-cm^3 Ge(Li) detector. The resolution of the Ge(Li) detector was about 4 keV full width at half maximum (FWHM) at 1.33 MeV (^{60}Co) and 25 keV at 8 MeV. Conventional electronics were associated with the NaI(Tl) detectors. The electronics associated with the Ge(Li) detector consisted of an Ortec model 118-A preamplifier, a Tennelec TC-200 amplifier, an Intertechnique CA-13 analog-to-digital converter (ADC), and a BM 96 4096-channel analyzer.

B. Charged Particle Experiment

The target was produced by evaporation of red phosphorus onto a 10–20-$\mu g/cm^2$ self-supporting carbon foil. The target thickness, 9.0 ± 0.3 $\mu g/cm^2$, was determined by low-energy proton Rutherford scattering in a resonance-free region. The beam intensity was kept below 300 nA. No target deterioration was observed. The optimum energy resolution was obtained by adjusting the beam optics[13] before the analyzing magnet. The energy resolution, measured at the 1.7476 ± 0.0009-MeV sharp resonance of the $^{13}C(p,\gamma)^{14}N$ reaction,[11] was found to be lying between 2.5×10^{-4} and 3×10^{-4}. The beam was stopped in the graphite lining of the Faraday cup located 150 cm downstream from the target.

The charged particles were detected by three surface-barrier detectors subtending solid angles of 0.55×10^{-3} sr and mounted in a 50-cm-diam scattering chamber.[14] All the events from the most backward detector were analyzed in order to observe the particle decay of the resonance levels. To minimize dead time, only the events from elastic scattering on ^{31}P were selected in the other detectors. The signals were amplified and routed through the ADC to a multiplexer system and a 4096-channel analyzer.

γ rays with energy greater than 3 MeV were recorded in the same experiment with a 3.8-$\times$3.8-cm NaI(Tl) detector placed inside the scattering chamber at 45° to the beam direction and at a distance of 5 cm from the target.

III. ANALYSIS

A. Ge(Li) Spectra

The energies of the γ rays were determined by means of a computer code. The input data for this program were the energies of some radioactive sources, the energy of the resonance level calculated from the proton energy and the Q value of the $^{31}P(p,\gamma)$ reaction ($Q=8.8639\pm0.0008$ MeV[15]), the energies of some γ-ray cascades through levels of known energy, and the corresponding peak positions. The efficiency curve was obtained from a ^{56}Co radioactive source for $E_\gamma \le 3.2$ MeV, and from the 1.555-MeV resonance of the ^{31}P-$(p,\gamma)^{32}S$ reaction[16] for $E_\gamma > 3.2$ MeV. This efficiency curve is assumed to be accurate to within 10%.

B. Angular-Distribution and Triple-Correlation Analysis

The experimental data were fitted to theoretical predictions for all spin combinations of the various members of the cascades. Pure octupole transitions have been discarded. In the $^{31}P+p$ reactions, only the $m=0$, ±1 magnetic substates of the resonance level can be populated. A FORTRAN code written for the Orsay 1108 Univac computer calculates the function

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

where $N_{i\,\mathrm{exp}}$ is the experimental value, $N_{i\,\mathrm{th}}$ is the theoretical one calculated with the formalism and the phase convention of Harris, Hennecke, and Watson,[17] and $\Delta N_{i\,\mathrm{exp}}$ is the experimental error. The population P_0 of the $m=0$ magnetic substate is varied from 0 to 1, and arctanδ, where δ is the mixing ratio, is varied from −90 to +90°. For all spin combinations a solution (P_0,δ) was accepted if it yielded a minimum for the Q^2 function below the 0.1% confidence limit. The errors on P_0 and δ were found by intersecting the Q^2 function with the horizontal line $Q^2=Q^2_{\mathrm{min}}+1$. Correction factors for the finite solid angle of the detectors were taken into account.

C. Elastic Proton Scattering Analysis

When protons are incident on a $J^\pi=\frac{1}{2}^+$ nucleus, only one continuous formation parameter is needed because of parity conservation. This formation parameter is either the orbital mixing for resonances with unnatural parity, or the channel-spin mixing for resonances with natural parity. Then the partial width Γ_p consists of at most two terms.

The theoretical formalism derived by Blatt and Biedenharn[18] was used. The beam energy spread and the finite target thickness were taken into account by folding an instrumental energy-resolution function into the theoretical expression. The resolution function was approximated by a nonsymmetric triangular shape[19–21] which accounts for the proton-energy straggling in the target. The dimensions of the triangle were deduced from the beam resolution and the target thickness.

Semiempirical phase shifts were used in the analysis instead of the conventional hard-sphere phase shifts because some inelastic and reaction channels are open. The semiempirical phase shifts were deduced from the elastic differential cross section in a structureless energy region. For this measurement, three detectors were positioned at angles corresponding to zeros of Legendre polynomials for $l=1$, 2, and 3, and a fourth detector at 166°. The following values in radians have been determined and used during the analysis: $\Phi_0 = \Phi_1 = -0.14$, $\Phi_2 = -0.03$, and $\Phi_3 = -0.01$. The values for Φ_4 and Φ_5 were set equal to zero. This procedure is believed to be realistic since the

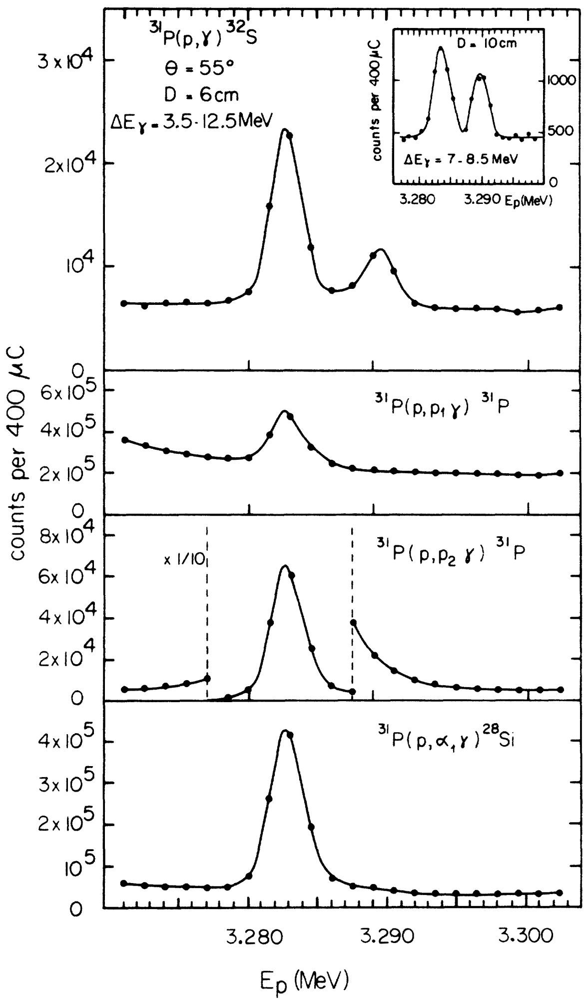

FIG. 1. γ-ray yield curves of the (p,γ), $(p,p_1\gamma)$, $(p,p_2\gamma)$, and $(p,\alpha_1\gamma)$ reactions on ^{31}P. The NaI(Tl) spectrometer was at 55° with respect to the beam direction and at a distance $D = 6$ cm from the target. Insert: γ-ray yield curve of the $^{31}P(p,\gamma)^{32}S$ reaction obtained by counting γ rays with energies between 7 and 8.5 MeV. This window includes the second step (8.126 → 0) of the main cascade decaying from the 12.050-MeV level. During this latter measurement the NaI(Tl) spectrometer was at a distance $D = 10$ cm from the target. Part of the resonance effect observed in the yield curve of the $^{31}P(p,p_2\gamma)^{31}P$ reaction may be due to the 2.23-MeV γ ray from the first level of ^{32}S fed in the decay of the resonance level. The yield curve of the $^{31}P(p,\alpha_1\gamma)^{28}Si$ is not corrected for a Compton contribution from the 2.23-MeV γ ray. The resonant effect in the $^{31}P(p,p_1\gamma)^{31}P$ is due to a Compton contribution from the 2.23- and 1.78-MeV γ rays.

background is well reproduced up to 3.3 MeV.

The experimental data were then compared to the theoretical values for a specified set of fixed parameters (total angular momentum J of the resonance level, orbital angular momentum l_p of the captured proton, and formation parameter). The minimum of the corresponding Q^2 function was searched for with respect to the resonance energy E_R, the proton partial width Γ_p, and the total width Γ by means of a FORTRAN code.[22] A group of values (E_R, Γ_p, Γ) was accepted if the corresponding Q^2 minimum was below the 0.1% confidence limit. The interferences between two or more resonances could also be analyzed by the code.

IV. EXPERIMENTAL RESULTS

A. Energies of Resonance

The yield curves (Fig. 1) of the (p,γ), $(p,p_1\gamma)$, $(p,p_2\gamma)$, and $(p,\alpha_1\gamma)$ reactions on ^{31}P have been measured in the same experiment with a thin target (11 ± 2 $\mu g/cm^2$) in the energy range $E_p = 3.27$–3.30 MeV. The γ rays were detected by a NaI(Tl) spectrometer located at 55° with respect to the beam direction and a distance of 6 cm from the target. The photopeaks of the 1.27-, 1.78-, and

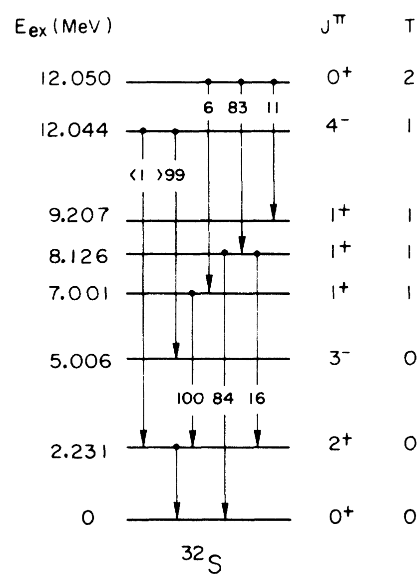

FIG. 2. γ-ray decay schemes of the 12.044- and 12.050-MeV ^{32}S levels. Branching ratios of the 8.126- and 7.001-MeV levels are from this work. The decay of the 9.207-MeV level is given in Ref. 25.

TABLE I. Electromagnetic decay properties of the 12.044-MeV ^{32}S level.

E_{ex} (MeV)	J^{π},T	$(2J+1)\Gamma_p\Gamma_\gamma/\Gamma$ (eV)	E_f (MeV)	J^{π},T	Branching ratio (%)	Mixing ratio	Radiation strengths [a] (W.u.) $M1$	$M2$ [b]
12.044 ± 0.004	$4^-,1$	7.0 ± 1.4	5.006	$3^-,0$	>99	0.00 ± 0.03	0.13 ± 0.03	
			2.231	$2^+,0$	<1	c		<0.7

[a] The Weisskopf radiative widths have been calculated using $r_0 = 1.2$ fm.
[b] The limit for the $M2$ strength has been derived assuming $\delta(E3/M2) = 0$.
[c] The mixing ratio $\delta(E3/M2)$ was not measured in the present work.

2.23-MeV γ rays were selected by means of three single-channel analyzers (SCA) to obtain the yield curves of the $(p,p_1\gamma)$, $(p,\alpha_1\gamma)$, and $(p,p_2\gamma)$ reactions, respectively. The γ rays with energies between 3.5 and 12.5 MeV were selected by means of a fourth SCA to obtain the yield curve of the $^{31}P(p,\gamma)^{32}S$ reaction. In this proton energy range where only one resonance was reported at 3.281 $\pm$ 0.004 MeV[23] two resonances were observed at 3.283 ± 0.003 and 3.289 ± 0.003 MeV. The corresponding excitation energies calculated with the Q value of Ref. 15 are 12.044 ± 0.004 and 12.050 $\pm$ 0.004 MeV. Only the 3.283-MeV resonance is seen in the $(p, x\gamma)$ reactions.

B. Decay Schemes

Ge(Li) γ-ray spectra have been recorded at the two resonance energies 3.283 and 3.289 MeV. Branching ratios are presented in Fig. 2 and Tables I and II. The 3.283 ± 0.003-MeV resonance observed in the present work may be identified with the 3.281 ± 0.004-MeV resonance[23] because a strong transition feeding the $J^{\pi} = 3^-$, 5.006-MeV state has been observed in the two experiments.

The Ge(Li) γ-ray spectrum taken at the 3.289-MeV resonance is presented in Fig. 3. The detector was at 90° with respect to the beam direction at a distance of 3.5 cm from the target. The transitions with energies below 8 MeV might not have been detected out of the Compton background if their branching ratios were less than approximately 3%. For γ-ray energies above 8 MeV, transitions with branching ratios as small as 1% were believed to be observable. The branching ratios of the transitions from the 12.050-MeV level are accurate to within 10% for the main component and 20% for the other ones.

If the 12.050-MeV level is the lowest $T=2$ state of ^{32}S as proposed in Ref. 8 it must decay through $T=1$ levels according to the basic electromagnetic slection rule[24] for γ decay which requires $\Delta T = 0, \pm 1$. This 12.050-MeV level feeds three levels at 7.001, 8.126, and 9.207 MeV. These energies are known within $\pm$ 0.004 MeV and are in good agreement with those determined by Coetzee, Meyer, and Reitmann[25] in a recent study of the $^{31}P(p,\gamma)^{32}S$ reaction. These levels correspond to those observed at 6.997 ± 0.010, 8.122 ± 0.015, and 9.207 $\pm$ 0.015 MeV by Graue *et al.*[26] in a study of the $^{31}P(^3He,d)^{32}S$ reaction. The 8.126-MeV level is the same as the one observed at 8.13 ± 0.07 MeV by Fagg *et al.*[27] in an electron scattering experiment.

TABLE II. Electromagnetic decay properties of the 12.050-MeV ^{32}S level.

E_{ex} (MeV)	J^{π},T	$(2J+1)\Gamma_p\Gamma_\gamma/\Gamma$ (eV)	E_f (MeV)	J^{π},T	Branching ratios (%) Exp.	Theor. [b]	Radiation strengths [a] $M1$ Exp. c	Exp. d	Theor. b	$E2$
12.050 ± 0.004	$0^+,2$	2.4 ± 0.5	7.001	$1^+,1$	6 ± 1	6	0.07 ± 0.02	0.053 ± 0.011	0.038	
			8.126	$1^+,1$	83 ± 8	83	2.1 ± 0.6	1.57 ± 0.31	0.89	
			9.207	$1^+,1$	11 ± 2	11	0.73 ± 0.20	0.55 ± 0.11	0.33	
			9.07 [e]	$1^+,1$		0.1			3×10^{-3}	
			2.231	$2^+,0$	≤ 0.8					≤ 0.06

[a] Weisskopf radiative widths have been calculated with $r_0 = 1.2$ fm.
[b] Reference 10.
[c] Calculated with $\Gamma_p/\Gamma = 0.75 \pm 0.20$.
[d] Calculated with $\Gamma_p/\Gamma = 1$.
[e] Theoretically predicted value for an experimentally unidentified level (Ref. 10).

The 7.001- and 8.126-MeV levels have been assigned $J^\pi = 1^+$ and identified as the analogs of the ground state and of the 1.149-MeV state of ^{32}P.[26] The γ-decay schemes of the 7.001- and 8.126-MeV levels (Fig. 2) are in good agreement with previous determinations.[25,28]

The 9.207-MeV level has been previously observed as a resonance level at 0.355 MeV in the ^{31}P(p,γ)^{32}S reaction and assigned $J = 1$.[29,30] If the 9.207-MeV level is also a $T = 1$ state it must be the analog of one of the three states at 2.175, 2.217, or 2.230 MeV in ^{32}P.[31]

A possible transition to the first excited level of ^{32}S will be discussed in Sec. V. A background from the ^{31}P(p,γ_0)^{32}S reaction has been previously noticed[32] in the proton energy range studied in this work. This background is responsible for the few counts observed in the γ_0 region.

C. Resonance Strengths

The resonance strengths $S = (2J+1)\Gamma_p\Gamma_\gamma/\Gamma$ (where J is the total angular momentum and Γ, Γ_p, and Γ_γ the total and partial widths of the resonance level) have been obtained for the two resonances from a careful measurement of the yield curve. A NaI(Tl) spectrometer was placed at 55° with respect to the beam direction and at a distance of 10 cm from a thin target. The yield curve was obtained by recording a γ-ray spectrum for each proton energy and by measuring the photopeak area of the most intense component in this spectrum.

The same target was used to derive the absolute strengths of the two resonances by comparison with the standard resonance strength $S = 0.52 \pm 0.08$ eV of the 0.642-MeV resonance observed in the ^{31}P(p,γ)^{32}S reaction.[33] As a check the two transitions 12.050 → 8.126 and 8.126 → 0 were used to obtain two yield curves for the 3.289-MeV resonance. The two determinations gave the same result within 4%. The resonance strengths $S = 7.0 \pm 1.4$ eV and $S = 2.4 \pm 0.5$ eV were deduced for the 3.283- and 3.289-MeV resonances, respectively (Tables I and II). The errors quoted in Tables I and II result from a quadratic addition of the errors in the photopeak-area measurement, the branching ratios, and the standard resonance strength.

D. Spin Measurements

In order to obtain information about the spin of the two resonances, γ-ray angular-distribution measurements were carried out and analyzed as described in Sec. III B. The information about the spin of the 3.283-MeV resonance will be useful in the analysis of the proton elastic scattering data (Sec. IV F). The 3.289-MeV resonance leading to the 12.050-MeV level must be $J^\pi = 0^+$ if it is the lowest $T = 2$ state of ^{32}S, which is the analog of the ground state of ^{32}Si. For any solution (J, P_0, δ)

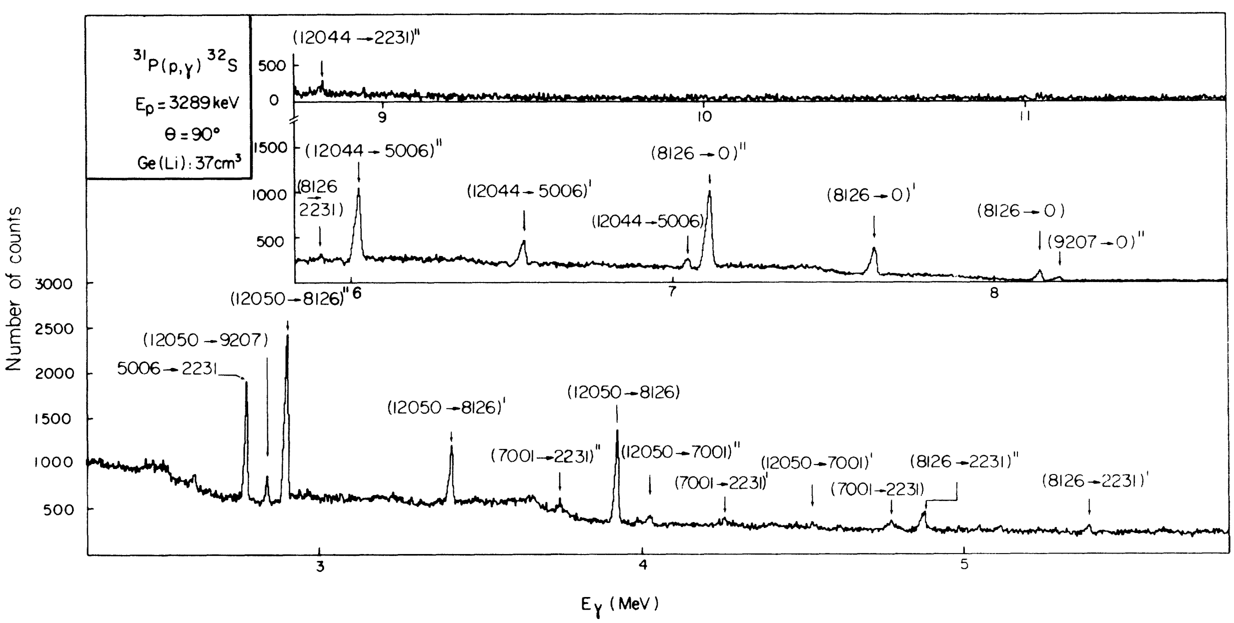

FIG. 3. Ge(Li) γ-ray spectrum at the $E_p = 3.289$-MeV resonance. Some transitions from the 12.044-MeV level are also observed. The unsymmetric shape of the high-energy peaks is attributed to neutron damage in the Ge(Li) detector. A total charge of 175 mC was collected during a 26-h measurement with a beam intensity lower than 2 μA.

the radiation strengths $|M(L)|^2=\Gamma_\gamma/\Gamma_w$, where Γ_γ is the radiative width and Γ_w the Weiskopf estimate of the $2L$-pole radiation were calculated from the resonance strengths and the branching ratios, and compared with the average values given by Skorka, Hertel, and Retz-Schmidt.[34] For this comparison a proton partial width $\Gamma_p/\Gamma=1$ was assumed, leading to a lower limit for $|M(L)|^2$.

1. 3.283-MeV Resonance

Two NaI(Tl) detectors located at 12.5 cm from the target were used to obtain the angular distribution of the transition feeding the $J^\pi=3^-$, 5.006-MeV level. One detector at 90° with respect to the beam direction was used as a monitor and the other one was successively placed at the four angles 0, 35, 55, and 90°. The experimental angular distribution was least-squares fitted with the function $W=1-(0.284\pm0.011)P_2(\cos\theta)$ and analyzed for J values ranging from 1 to 5. The solutions (P_0, δ) for $J=1$ lead to considerable octupole transition strengths and therefore are ruled out. So are ruled out the solutions (P_0, δ) for the $J^\pi=2^+$ and $J^\pi=3^+$ values which yield $M2$ tran-

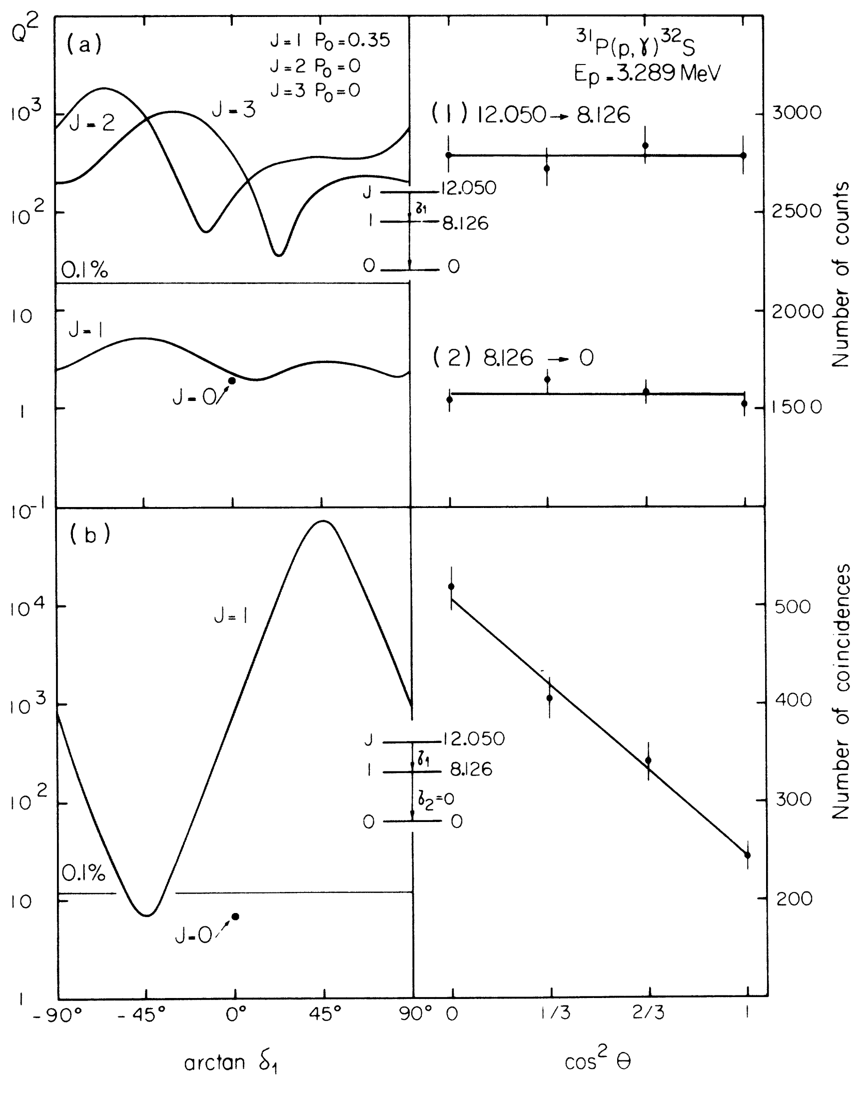

FIG. 4. (a) γ-ray angular distributions of the two members of the main cascade, measured at $E_p=3.289$ MeV with a Ge(Li) detector. The results of the simultaneous analysis of these two angular-distribution measurements are shown on the left-hand part of the figure. (b) Triple angular-correlation measurements in the Litherland and Ferguson geometry II for the 12.050 MeV → 8.126 MeV → 0 cascade. The curve is from a least-squares fit to the experimental data. The result of the analysis for $J=0$ ($P_0=1$, $\delta_1=0$) and $J=1$ ($P_0=0.35$ and δ_1 variable) is shown on the left-hand part of the figure.

sition strengths which are too high. In the case $J=4$, for any value of P_0 a solution is obtained for $\delta=0$. No solution could be found for the $J=5$ value. In conclusion the J^π values for the 3.283-MeV resonance must be limited to 2^-, 3^-, $4^\pm$. The angular distribution of the weak transition to the first excited state has not been analyzed.

2. *3.289-MeV Resonance*

For this γ-ray angular-distribution measurement the Ge(Li) detector was used and located at 6 cm from the target and at angles of 0, 35, 55, and 90° with respect to the beam direction. A NaI(Tl) spectrometer was used as a monitor. The isotropic angular distributions of the primary and secondary components of the main cascade through the 8.126-MeV level can be seen in Fig. 4(a). Both angular-distribution measurements were simultaneously analyzed for J values ranging from 0 to 3. The analysis was limited to the combination $P_0=1$ and $\delta=0$ for the $J=0$ value. The result of the analysis is shown in the left-hand part of Fig. 4(a). The $J=2$ and $J=3$ values are ruled out for any combination of P_0 and δ. The $J=1$ ($P_0=0.35 \pm 0.05$, $-\infty<\delta<+\infty$) and $J=0$ values gave possible solutions.

A triple correlation measurement of the two members of this main cascade was performed [Fig. 4(b)] in the geometry II of Litherland and Ferguson.[35] Two NaI(Tl) detectors were used. The analysis was carried out for the two possible values $J=0$ ($P_0=1$, $\delta_1=0$) and $J=1$ (P_0 and δ_1 variable). The result of this analysis is shown in the left-hand part of Fig. 4(b).

For the $J=1$ value the same population parameter ($P_0=0.35 \pm 0.05$) was also obtained from this analysis and a satisfactory minimum of Q^2 was found for $\delta_1=-1.00 \pm 0.15$. Odd parity leading to $|M(M2)|^2>2300$ Weisskopf units (W.u.) is discarded. Even parity leads to a $E2/M1$ mixed transition. The $M1$ transition strength is 0.26 ± 0.04 W.u. and is characteristic of a $\Delta T=1$ transition.[34] However, the $E2$ transition strength is 72 ± 21 W.u. Such a strength is greater by 2 orders of magnitude than the mean value of 0.5 W.u. given by Skorka, Hertel, and Retz-Schmidt[34] for $\Delta T=1$, $E2$ transitions. Thus the $J=1$ value is

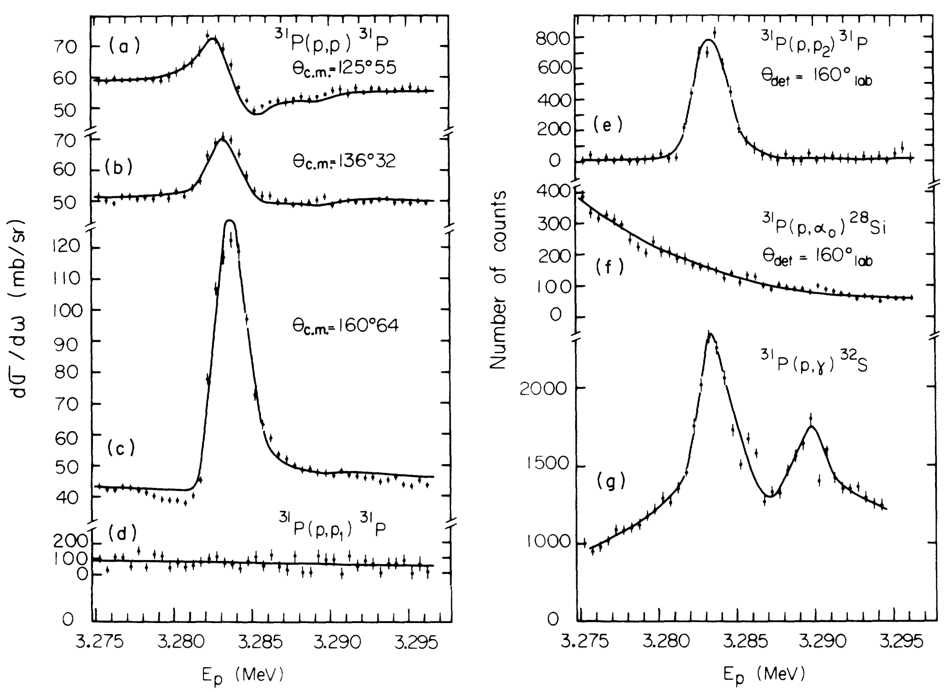

FIG. 5. The yield curves of the $^{31}P(p,p)^{31}P$ reaction measured at $\theta_{lab}=124$, 135, and 160° are presented on the three curves, labeled, respectively, (a), (b), and (c). The yield curves of $^{31}P(p,p_1)^{31}P$, $^{31}P(p,p_2)^{31}P$, and $^{31}P(p,\alpha_0)^{28}Si$ reactions measured at $\theta_{lab}=160°$ are presented in the curves labeled (d), (e), and (f), respectively. γ-ray yield curve of the $^{31}P(p,\gamma)^{32}S$ reaction shown in part (g) has been measured during the same experiment using a 3.8-×3.8-cm NaI(Tl) detector placed inside the scattering chamber at 45° to the beam and at $D=5$ cm from the target. For the three curves (a), (b), and (c), the line has been drawn with the following parameters: $E_p=3.283$ MeV, $\Gamma=470$ eV, $\Gamma_p/\Gamma=0.8$; and $E_p=3.289$ MeV, $\Gamma=100$ eV, $\Gamma_p/\Gamma=0.75$. The arbitrary value $\Gamma=100$ eV was used since an upper limit was only derived from this experiment.

ruled out.

For the $J=0$ value, the strong dipole radiation strengths deduced are typical of $\Delta T=1$ transitions, so that the 9.207-MeV level is assigned $T=1$, the same isospin as for the 7.001- and 8.126-MeV levels. If even parity is assumed the $M1$ radiation strengths (Table II) are of the same magnitude as the ones observed in the decay of the first $T=2$ states of ^{20}Ne, ^{24}Mg, and ^{28}Si.[36] However, odd parity which yields an $E1$ radiation strength $|M(E1)|^2=(5\pm1)\times10^{-2}$ W.u. for the main transition cannot be ruled out according to the histograms of Skorka, Hertel, and Retz-Schmidt.[34]

E. Isospin of the 12.050-MeV Level

Though the parity was not directly measured, there are arguments from the present work to identify the 12.050-MeV level with the lowest $J^\pi, T=0^+,2$ level observed in the $^{34}S(p,t)^{32}S$ reaction.[1] These arguments can be summarized as follows:

(1) The excitation energy from this work, 12.050 ± 0.004 MeV, is in good agreement with the 12.034 ± 0.040-MeV value obtained in the transfer reaction.

(2) The total angular momentum of the level is $J=0$.

(3) The strength of the observed dipole transitions is typical of $\Delta T=1$ transitions.

(4) The three levels involved in the γ decay are $T=1$.

From the two last points isospin $T=0$ or 2 could be assigned to the 12.050-MeV level. Further information can be obtained by considering the similar γ-decay schemes of the levels at 12.050 MeV in ^{32}S and at 5.073 MeV in ^{32}P.[37,38] In the γ decay of the 5.073-MeV level of ^{32}P for which even parity has been established[38] the ground state, and the 1.149- and 2.230-MeV states are fed with the same branching ratios as the 7.001-, 8.126-, and 9.207-MeV levels fed in the γ decay of the 12.050-MeV level of ^{32}S. As indicated in Sec. IV B the ground state and the 1.149-MeV state of ^{32}P are the parent states of the 7.001- and 8.126-MeV levels of ^{32}S. Such similar γ-decay schemes are characteristic of the $\Delta T=1$ decay of two analog levels.[39] In the present work the $\Delta T=1$ character of the transitions has been established for the 12.050-MeV level. The 12.050-MeV level of ^{32}S is therefore the analog of the 5.073-MeV one of ^{32}P. The $J=1$, 9.207-MeV level of ^{32}S is the analog of the 2.230-MeV level of ^{32}P, and they are assigned $J^\pi=1^+$ since no odd-parity level has been observed in ^{32}P up to this energy.[31]

The two levels at 12.050 MeV in ^{32}S and 5.073 MeV in ^{32}P have therefore J^π, $T=0^+,2$ for two reasons: First, the ^{32}S level has been assigned a $J=0$ value and the ^{32}P one is known to have even parity; second, only a $T=2$ level can feed $T=1$ levels in ^{32}P with $\Delta T=1$ transitions.

F. Total and Partial Widths

The yield curves of the (p,p_0), (p,p_1), (p,p_2), and (p,α_0) reactions on ^{31}P were measured at three angles ($\theta_{lab}=124$, 135, and 160°) for the first reaction and at $\theta_{lab}=160°$ for the other ones (Fig. 5). The $^{31}P(p,\alpha_1)^{28}Si$ reaction was not studied because the α_1 group is at about the same energy as protons from the $^{16}O(p,p)^{16}O$ reaction. The decreasing α_0 yield is due to a broad resonance of the $^{31}P(p,\alpha_0)^{28}Si$ reaction at 3.254 MeV.[40] At the 3.283-MeV resonance the p_0 and p_2 channels are strongly resonant. For this resonance the experimental results from the (p,p_0) reaction have first been analyzed using a one-level formula. The $J^\pi=2^-,3^-$, and $4^\pm$ values have been considered in the analysis (Sec. IV D). The experimental results are simultaneously accounted for at the three angles with only the $J^\pi=4^-$, $l_p=3$, and $s=1$ set of values. The results are presented in Table III. The partial widths Γ_{p_2}/Γ and Γ_{α_1}/Γ have been derived from the resonance strength $(2J+1)\Gamma_p\Gamma_{p_2}/\Gamma=435\pm87$ eV. Isospin $T=1$ is then derived for this level from the transition strength (Table I).

No resonance effect could be easily detected in the p_0 channel at the 3.289-MeV resonance and only an upper limit could be determined for the total width of this resonance. In order to obtain this upper limit all the experimental points were analyzed using a two-level formula. The com-

TABLE III. Properties of the particle decay of the 12.044- and 12.050-MeV levels.

E_p (MeV)	E_{ex} (MeV)	J^π, T	Γ [a] (eV)	Γ_{p_0}/Γ	Γ_{p_2}/Γ	Γ_{α_0}/Γ	Γ_{α_1}/Γ	θ_p^2
3.283 ± 0.003	12.044 ± 0.004	4^-, 1	470 ± 50	0.80 ± 0.10	0.13 ± 0.05		0.07 ± 0.03	5.6×10^{-3}
3.289 ± 0.003	12.050 ± 0.004	0^+, 2	<170	1				$<8\times10^{-5}$
			<230	0.75 ± 0.20 [b]		0.16 ± 0.08 [b]	0.09 ± 0.05 [b]	

[a] The two values for the total width of the 12.050-MeV level were derived using the two values for the proton partial width $\Gamma_p/\Gamma=0.75$ and $\Gamma_p/\Gamma=1$ in the analysis of the proton elastic scattering data (Sec. IV F).

[b] The values of these partial widths are from Ref. 2.

puter code (Sec. III C) calculates the Q^2 function with respect to the total width Γ. A proton partial width $\Gamma_p/\Gamma = 0.75$ (Ref. 2) was used during the analysis for the 3.289-MeV resonance. The Γ value which makes the Q^2 function equal to the 0.1% confidence limit is adopted as the upper limit. A total width $\Gamma \leq 230$ eV was derived in this way.

In the present work no resonance was observed in the (p, α_0) and $(p, \alpha_1\gamma)$ reactions. This is in contradiction with the results from Ref. 2. This disagreement can be accounted for in two ways. First the total width could be substantially smaller than 230 eV, and the resonant effect obtained by combining the total width and the partial width from Ref. 2, $\Gamma_{\alpha 0}/\Gamma = 0.16$, would be unobservable in the background of α particles from the 3.254-MeV resonance. On the other hand, since the partial widths of Ref. 2 are obtained from long and difficult particle-triton coincidence experiments with very low statistics (at least for the two α partial widths), these two widths could have been overestimated. In order to account for this possibility another analysis of the proton elastic scattering data was carried out with the extreme proton partial width $\Gamma_p/\Gamma = 1$. The upper limit of the total width obtained in this way was 170 eV.

The proton reduced width θ_p^2, in $\hbar^2/\mu a^2$ units, is less than 8×10^{-5}. This strong hindrance in the formation of the resonance level in the $^{31}P + p$ channel is indicative of high isospin purity for the 12.050-MeV level. The properties of the particle decay of the two levels at 12.044 and 12.050 MeV are summarized in Table III.

V. DISCUSSION

The electromagnetic properties of the 12.050-MeV level were compared with the theoretical predictions[10] (Table II). These calculations do not require the use of effective $M1$ operators and show that the predominant decay mode through the 8.126-MeV level given in terms of configuration amplitudes is

$$-0.62[(d^{12}_{5/2})_{00}(s^{2}_{1/2})_{01}(d^{2}_{3/2})_{01}]_{02}$$
$$-0.62[(d^{12}_{5/2})_{00}(s^{2}_{1/2})_{10}(d^{2}_{3/2})_{01}]_{11}$$
$$-0.30[(d^{12}_{5/2})_{00}(s^{2}_{1/2})_{01}(d^{2}_{3/2})_{01}]_{00}.$$

The agreement is excellent as far as the branching ratios to the 7.001-, 8.126-, and 9.207-MeV levels are concerned.[10] The weak branch to a level predicted to lie at 9.07 MeV is below the experimental sensitivity. The experimental values of the $M1$ radiation strengths are greater than the theoretical ones even using the value $\Gamma_p/\Gamma = 1$. The agreement might be better if the amplitudes of the first two configurations quoted above were larger than indicated in Ref. 10. A $\Delta T = 2$ forbidden γ transition from the 12.050-MeV level (J^π, $T = 0^+, 2$) to the first excited state at 2.231 MeV (J^π, $T = 2^+, 0$) was searched for. It was not possible to separate the γ transitions from the 12.044- and 12.050-MeV levels to the 2.231-MeV level. A contribution from the 3.283-MeV resonance was estimated and subtracted from the 90° spectrum, taken at the 3.289-MeV resonance. No measurement was made off resonance. An upper limit of 0.8% can be put to a branch towards the first excited state of ^{32}S leading to an $E2$ strength (Table II) less than 0.06 W.u. Such an $E2$ strength is comparable to the $E2$ strengths of the corresponding γ decay of the lowest $T = 2$ state in ^{24}Mg and ^{28}Si.[36]

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