Investigation of Four Resonances in the Reaction $Si^{29}(p,\gamma)P^{30}$

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Thin Si^{29} targets have been bombarded with protons from a Cockcroft-Walton generator in the energy region $E_p=0.2$ to 0.8 Mev. The gamma radiation from the $Si^{29}(p,\gamma)P^{30}$ reaction has been investigated with a NaI scintillation spectrometer at the 326-, 414-, 693,- and 729-kev resonances. Pulse spectra taken at each resonance at angles of $\theta=0$ and $\theta=90$ degrees to the proton beam were analyzed with a 70-channel Hutchinson-Scarrott kicksorter. The decay of the resonance levels was further investigated by γ-γ coincidence measurements.

The following spins, J, parities, and isobaric spins, T, could be assigned to P^{30} levels: Ground state, $J=1^+$, $T=0$; 0.684 Mev, $J=0^+$, $T=1$; 0.706 Mev, $J=1^+$, $T=0$; 1.45 Mev, $J=(2^+)$, $T=0$; 2.94 Mev, $J=2^+$, $T=1$; 4.18 Mev, $J=2^+$, $T=1$; 5.88 Mev, $J=2^-$, $T=1$; 5.96 Mev, $J=1^-$, $T=0$; 6.23 Mev, $J=1^-$, $T=1$; 6.27 Mev, $J=3^-$, $T=0$. The reaction Q value is measured as $Q=5.570\pm0.030$ Mev.

From absolute gamma-ray yield measurements, the radiation widths of all resonance levels could be determined. These levels are shown to have T as a good quantum number. The strong gamma rays are of $E1$ character and satisfy the isobaric-spin selection rule for self-conjugate nuclei.

I. INTRODUCTION

IN a previous communication,[1] preliminary results concerning the position, spin, parity, and isobaric spin of the ground state and the first excited state in P^{30}, as obtained from an investigation of two resonances in the $Si^{29}(p,\gamma)P^{30}$ reaction, were given. The assignment of spins and parities was based on gamma-transition probabilities. The results of these experiments have been confirmed by Broude *et al.*[2] by more elaborate measurements, including those of angular distributions.

Recently, Lee and Mooring[3] have reported experiments on the $S^{32}(d,\alpha)P^{30}$ reaction which raised doubt concerning the isobaric spin assignment of the first excited state. A more thorough examination of the P^{30} nucleus has now been carried out both by the $S^{32}(d,\alpha)P^{30}$ and the $Si^{29}(p,\gamma)P^{30}$ reactions. The first of these reactions is treated in the preceding paper[4]; the second is dealt with in this communication.

For $E_p=200$ to 800 kev, the $Si^{29}(p,\gamma)P^{30}$ reaction shows four resonances at proton energies of 326, 414, 693, and 729 kev.[5–8] The gamma-ray spectrum at each resonance has been analyzed with NaI scintillation spectrometers. The decay schemes of the resonance levels with their branching ratios, and the spins, parities, and isobaric spins of several levels have been found by a combination of the analysis of single spectra, coincidence measurements, and angular-distribution measurements.

II. EXPERIMENTAL METHOD

The Utrecht 800-kev Cockcroft-Walton generator provided a proton beam of up to 10 μa after 30-degree magnetic deflection. During the experiments to determine the proton resonance energies, a beam-defining slit of 1 mm was used at a distance of 5 cm from a $Si^{29}O_2$ target of 16 $\mu g/cm^2$. This resulted in resonance half-widths of about 12 kev. For the other experiments, a 3-mm slit and a 50-$\mu g/cm^2$ target resulted in a higher yield. Both targets were enriched by electromagnetic separation at the Atomic Energy Research Establishment, Harwell, England.

The gamma radiation was detected with two cylindrical NaI crystals, $1\frac{5}{8}$ in. in diameter and 2 in. thick, mounted on DuMont 6292 photomultiplier tubes. A 70-channel Hutchinson-Scarrott pulse-height analyzer was used in combination with a single-channel differential discriminator. The half-width of the peaks amounted to 10% at $E_\gamma=0.5$ Mev and to 6% in the $E_\gamma=4$- to 6-Mev region.

For the measurements of single gamma spectra, the NaI crystal was brought as close to the target as possible. A circulating-oil system kept the temperature of the target at about 40°C in order to prevent evaporation of the target material. The assembly was surrounded by a lead box with 10-cm walls to suppress the background (mainly x-rays from the acceleration tube and 1.46-Mev gamma rays from the K^{40} in the walls of the target room). In this part of the experiments, the slits defining the proton beam were placed 25 cm from the target outside the lead box in order to reduce the background from the $C^{12}(p,\gamma)N^{13}$ and $C^{13}(p,\gamma)N^{14}$ reactions.

An analogous arrangement was used for the coincidence measurements where two crystals were placed

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[1] Endt, Kluyver, and van der Leun, Phys. Rev. **95**, 580 (1954).
[2] Broude, Green, Singh, and Willmott, Phys. Rev. **101**, 1052 (1956).
[3] L. L. Lee and F. P. Mooring, Phys. Rev. **104**, 1342 (1956).
[4] P. M. Endt and C. H. Paris, Phys. Rev. **110**, 89 (1958), preceding paper.
[5] R. Tangen, Kgl. Norske Videnskab. Selskabs, Forh. Skrifter (1946).
[6] J. C. Kluyver and P. M. Endt, *Proceedings of the Conference on Electromagnetically Enriched Isotopes and Mass Spectroscopy, Harwell, 1955*, edited by M. L. Smith (Academic Press, Inc., New York), p. 131.
[7] Milani, Cooper, and Harris, Phys. Rev. **99**, 645 (1955) and verbal report to Nuclear Data Group.
[8] Broude, Green, Singh, and Willmott, Physica **22**, 1139 (1956); Nuclear Data Card 56–9–43 (National Research Council, Washington, D. C.); and private communication.

at about 2.5 cm from the target. They were shielded from each other by a 2-cm lead block to avoid false coincidences from scattered gamma rays and annihilation radiation. The pulse spectrum from counter 1 in coincidence with pulses from counter 2 selected with a single-channel analyzer was displayed on the screen of the pulse-height analyzer. The resolution time of this arrangement was about 4 μsec.

Details of the target assembly used for the measurements of gamma-ray angular distributions have been given in an earlier paper.[9] One counter, placed as close to the target as possible, counted all pulses above a fixed energy (usually 1 Mev) and was used as a monitor. The pulses from the other counter, mounted at a distance of 4.5 cm at either zero or 90 degrees to the proton beam, were fed into the kicksorter. In order to correct for possible eccentricity of the target spot, the known isotropic angular distribution of the 6.14-Mev gamma rays at the $E_p=334$ kev $F^{19}(p,\alpha\gamma)O^{16}$ resonance and those of the gamma rays at the $E_p=454$ kev $Mg^{26}(p,\gamma)Al^{27}$ resonance[9] were used for calibration. During these measurements, the NaI crystals were shielded by only 3 mm of lead.

III. METHOD OF ANALYSIS

The gamma-ray yield curve (Fig. 1) shows four distinct resonances at proton energies of 328, 411, 700, and 731 kev, all ±10 kev. These values are in good agreement with other measurements.[5–8] Throughout this paper, the average values of 326, 414, 696, and 729 kev, as adopted by Endt and Braams,[10] will be used. The continuous background of Fig. 1 disappears partly with the lead shielding used in other experiments (see Sec. II).

At each of the four resonances, several single spectra have been measured in the way described in Sec. II. Generally, no special attempt has been made to determine the gamma-ray energies precisely, since the levels of P^{30} are known with precision from the magnetic analysis of alpha groups from the $S^{32}(d,\alpha)P^{30}$ reaction[4] to an extent not obtainable by scintillation spectrometer measurements. To get an independent determination of the $P^{30}-Si^{29}$ mass difference, the most intense gamma-ray cascade at each of the four resonances has been measured more carefully. The average Q value of the $Si^{29}(p,\gamma)P^{30}$ reaction thus found amounts to $Q=5.570\pm0.030$ Mev, giving a $P^{30}-Si^{29}$ mass difference of 2.015 ± 0.030 Mev, and a P^{30} mass excess of -11.315 ± 0.031 Mev, in good agreement with other determinations.[4] A Si^{29} mass excess of -13.330 ± 0.009 Mev was used.[10] Measurements of the energy of the lowest energy gamma rays are described in Sec. V.

To determine the relative intensities of the gamma

[9] Van der Leun, Endt, Kluyver, and Vrenken, Physica **22**, 1223 (1956).
[10] P. M. Endt and C. M. Braams, Revs. Modern Phys. **29**, 683 (1957).

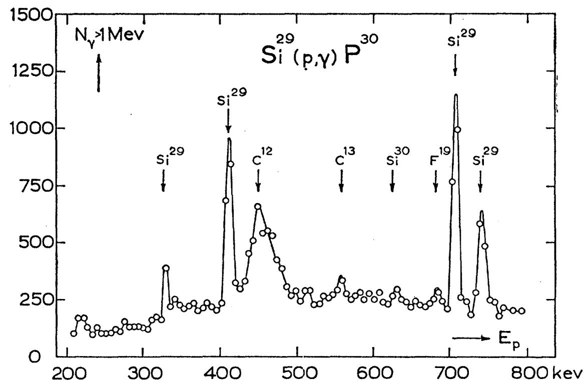

FIG. 1. Gamma-ray yield from proton bombardment of a thin Si^{29} target.

rays, the background spectrum was measured with the generator off; or, if necessary in view of gamma rays from (p,γ) reactions on the C^{12}, C^{13}, and F^{19} contaminants, the spectrum was measured at proton energies just below and above the resonance energy. After subtraction of the background, the remaining spectrum was analyzed into single gamma rays with the help of standard spectra.[11] After correction for the absorption in the copper and nickel of the target holder and the target backing, the relative intensities were calculated taking into account the detection efficiency of the NaI crystal.[11]

The single gamma-ray spectra have been measured at an angle of $\theta=55$ degrees. The angle thus chosen has the advantage that the observed intensity is equal to the average intensity integrated over 4π if no terms higher than $\cos^2\theta$ occur in the angular distribution.

Gamma-ray anisotropies were measured by analyzing spectra measured at zero and 90 degrees, taking into account eccentricity of the target spot and finite angular resolution. These spectra gave additional information on gamma-ray intensities if properly corrected for anisotropy.

In some cases, coincidence measurements gave a corroboration of the proposed decay scheme. Moreover, these measurements sometimes gave additional information on relative intensities.

IV. GAMMA-RAY ANGULAR DISTRIBUTIONS

The angular distributions to be expected for the gamma rays of the $Si^{29}(p,\gamma)P^{30}$ reaction are computed from the tables of Sharp *et al.*[12] for channel spins $J_c=0$ and $J_c=1$ (the ground-state spin of Si^{29} being $J=\frac{1}{2}$). In some cases, mixing of proton orbital momenta can occur. If only pure dipole radiation is considered, the gamma-ray angular distribution must have the form: $W(\theta)=1+A\cos^2\theta$. The theoretical anisotropies, A, computed for s, p, d, and f capture, are collected in

[11] Kluyver, van der Leun, and Endt, Physica **20**, 1287 (1954).
[12] Sharp, Kennedy, Sears, and Hoyle, Atomic Energy of Canada, Limited, Report AECL-97, Chalk River, 1953.

TABLE I. Anisotropies computed for pure dipole radiation.

J_c	l_p	J_r	J_f	A
0	0	0^+	0	...
			1	0
1	1	0^-	0	...
			1	0
1	0	1^+	0, 1, 2	0
1	2	1^+	0	−0.60
			1	+0.43
			2	−0.07
0	1	1^-	0	−1.00
			1	+1.00
			2	−0.14
1	1	1^-	0	+1.00
			1	−0.33
			2	+0.08
0	2	2^+	1	−0.60
			2	+1.00
			3	−0.20
1	2	2^+	1	−0.33
			2	+0.43
			3	−0.10
1	1	2^-	1	−0.45
			2	+0.64
			3	−0.14
1	3	2^-	1	−0.50
			2	+0.75
			3	−0.16
1	2	3^+	2	−0.44
			3	+0.82
			4	−0.20
1	4	3^+	2	−0.45
			3	+0.86
			4	−0.21
0	3	3^-	2	−0.50
			3	+1.00
			4	−0.23
1	3	3^-	2	−0.39
			3	+0.69
			4	−0.18

Table I. The channel spin is indicated by J_c, the proton orbital momentum by l_p, the spin of the resonance level by J_r, and the spin of the final state by J_f.

The influence of the mixing of gamma-ray multipolarities will be treated under the discussion of the experimental results in Sec. VI.

Low-energy gamma rays are always superimposed on the Compton distributions of higher energy gamma rays. This makes it difficult to measure the angular distribution of the former. In a few cases, however, it has been possible to obtain some estimate of the anisotropy

TABLE II. Anisotropies computed for the second gamma ray of a gamma-ray cascade, assuming pure dipole or quadrupole transitions.

J_c	l_p	J_r	l_1	J_2	l_2	J_2	A
1	1	2^-	1	1	1	0	−0.45
1	1	2^-	1	1	1	1	+0.29
1	1	2^-	1	2	1	1	−0.24
1	1	2^-	1	3	2	1	+0.62
0	3	3^-	1	2	2	0	+1.00
1	3	3^-	1	2	2	0	+0.78
0	3	3^-	1	2	1	1	−0.50
1	3	3^-	1	2	1	1	−0.39

of the second gamma ray of the gamma-ray cascade following proton capture. Some anisotropies of the second gamma ray have been computed for pure dipole radiation of the first gamma ray and pure dipole, or quadrupole radiation, of the second gamma ray in the cascade. Then the angular distribution must have the general form: $W(\theta)=1+A_1\cos^2\theta+A_2\cos^4\theta$. The value of $A=A_1+A_2$ is given in Table II. The notations J_c, J_r, J_1, and J_2 are used for the channel spin, the spin of the resonance level, the spin of the intermediate level, and the spin of the final level; while l_p, l_1, and l_2 are used for the proton orbital momentum and for the multipolarity of the first and of the second gamma ray.

V. 700-kev DOUBLET

A general remark concerning the two lowest levels in P^{30} has to precede the separate discussion of the results at each resonance. From (p,γ) measurements

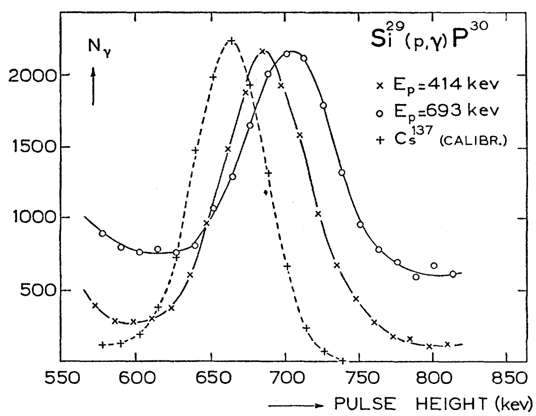

FIG. 2. Low-energy part of the scintillation spectrum taken at two different resonances (E_p=414 and 693 kev), showing the 700-kev doublet, together with the E_γ=661.6-kev calibration line of Cs^{137}.

at the 414-kev resonance, a level at 688±7 kev had been found with $J=0^+$ and $T=1$.[1,2] A strong alpha group found from the $S^{32}(d,\alpha)P^{30}$ reaction, leading to a 693-kev level, raised doubt about the $T=1$ assignment[3] since intense alpha groups are expected to correspond with $T=0$ levels. With the higher precision of the MIT magnetic spectrograph, a strong alpha group was found corresponding to a level at 708±8 kev in P^{30}.[4] Because of the disagreement between these values for the excitation energy, a precision measurement of the lowest energy gamma ray was undertaken at each of the four resonances. Repeated runs alternating with calibration runs with the 661.6-kev gamma ray from Cs^{137} gave energies of 703±6, 686±4, 705±5, and 686±6 kev at the 326-, 414-, 696-, and 723-kev resonances, respectively (Fig. 2). Clearly, the gamma-ray energy measured at the 326- and 696-kev resonances is different from that observed at the 414- and 723-kev resonances. A doublet structure, of which the lowest

TABLE III. Gamma rays observed at the $E_p=326$-kev resonance.

E_γ (Mev) experimental	E_γ (Mev) computed from reference 4	Transition	Intensity number of photons per 100 captures	Anisotropy $\left(\frac{I(0°)-I(90°)}{I(90°)}\right)$
5.87 ±0.04	5.877	(r) → (0)	86±8	−0.45±0.03
5.16 ±0.06	5.169	(r) → (2)	9±3	−0.45±0.10
4.41 ±0.06	4.426	(r) → (3)	5±2	
1.45 ±0.02	1.451	(3) → (0)	5±2	−0.66±0.40
0.703±0.006	0.708	(2) → (0)	10±3	+0.40±0.15

level has $T=1$ and the higher one $T=0$, resolves the contradictions mentioned above. Angular-distribution measurements (Sec. VI) confirm this assumption, as do subsequent measurements on the $S^{32}(d,\alpha)P^{30}$ reaction, from which a weak alpha group is found corresponding to a (680±10)-kev level.[4]

As to the energy determination from the (p,γ) reaction, a mixture of both low-energy gamma rays at one or more of the resonances cannot be excluded. However, the width of the photopeaks, as observed at each of the four resonances, was exactly that to be expected for a single gamma ray. In Sec. VI, other arguments will be put forward to prove that each resonance level predominantly decays to one of the two lowest excited states. The combined results of the (p,γ) and (d,α) reaction measurements[4] finally give the following averaged excitation energies:

$$\text{Level (1): } 684\pm4 \text{ kev, } T=1;$$

$$\text{Level (2): } 706\pm4 \text{ kev, } T=0.$$

The energy difference of 4.949±0.015 Mev between level (1) in P^{30} and the ground state of Si^{30} agrees very well with the value (4.935±0.020 Mev) computed from the Coulomb energy difference, taking into account the neutron-proton mass difference. The nuclear radius used to calculate the Coulomb energy difference was obtained by interpolation between the radii of neighboring $A=4n+1$ and $A=4n+2$ nuclei. The $A=4n+3$ nuclei give a distinctly higher Coulomb energy difference because of the proton-pairing effect.

VI. DISCUSSION OF THE RESULTS

The gamma rays observed at each of the four resonances are listed in Tables III through VI. The observed gamma-ray energies may be compared to the

TABLE IV. Gamma rays observed at the $E_p=414$-kev resonance.

E_γ (Mev) experimental	E_γ (Mev) computed from reference 4	Transition	Intensity number of photons per 100 captures	Anisotropy $\left(\frac{I(0°)-I(90°)}{I(90°)}\right)$
5.94 ±0.10	5.962	(r) → (0)	6±2	+0.45±0.30
5.30 ±0.05	5.282	(r) → (1)	90±8	−0.22±0.04
4.50 ±0.06	4.511	(r) → (3)	1±0.5	
2.99 ±0.06	{3.025 {2.937	(r) → (8)} (8) → (0)}	4±1	
2.28 ±0.06	2.257	(8) → (1)	weak	
1.46 ±0.02	{1.486 {1.451	(8) → (3)} (3) → (0)}	3±1	
0.686±0.004	0.680	(1) → (0)	98±10	−0.09±0.06

TABLE V. Gamma rays observed at the $E_p=693$-kev resonance.

E_γ (Mev) experimental	E_γ (Mev) computed from reference 4	Transition	Intensity number of photons per 100 captures	Anisotropy $\left(\frac{I(0°)-I(90°)}{I(90°)}\right)$
6.24 ±0.10	6.232	(r) → (0)	2±0.5	
5.54 ±0.08	5.524	(r) → (2)	2±0.5	
4.76 ±0.08	4.781	(r) → (3)	2±0.5	
4.27 ±0.03	4.260	(r) → (4)	35±5	−0.23±0.15
3.74 ±0.06	3.694	(r) → (5)	21±5	
3.55 ±0.06	3.509	(r) → (6)	29±6	
3.44 ±0.06	3.393	(r) → (7)	9±6	
2.78 ±0.05	2.839	(7) → (0)	7±5	
2.68 ±0.05	2.723	(6) → (0)	23±5	
2.54 ±0.03	2.538	(5) → (0)	21±4	
1.98 ±0.03	1.972	(4) → (0)	19±4	
1.83 ±0.05	1.830	(5) → (2)	3±1	
1.47 ±0.03	1.451	(3) → (0)	1±0.5	
1.26 ±0.01	1.264	(4) → (2)	15±5	
0.705±0.005	0.708	(2) → (0)	21±5	

energy differences measured from the $S^{32}(d,\alpha)P^{30}$ reaction with a precision of about 10 kev,[4] which are given in column 2. In the discussion of the resonances, the values of column 2 are used, rounded off to 10 kev. The numbering of the P^{30} levels in column 3 is shown in Fig. 6; the resonance levels are indicated by (r). The intensities given in column 4 as numbers of photons per 100 captures were averaged from the results of the analysis as described in Sec III. The intensities given in the tables are consistent within the experimental errors to the extent that the sum of the intensities of gamma rays de-exciting a particular level is equal to the total strength of gamma rays decaying to the same level.

a. $E_p=326$-kev Resonance

At this resonance, the ground-state transition dominates all others (see Table III). The $T=0$ ground state of P^{30} is, according to the shell model, expected to have $J=0^+$ or 1^+, although $J=1^+$ is more probable from analogy with the ground state of the deuteron. A weak 2.24-Mev gamma ray has recently been observed[13] in the β^+ decay of P^{30}. This fixes the P^{30} ground-state spin as 1^+ if the spin of the first excited state in Si^{30} is assumed to be 2^+. In addition to the empirical rule that the first excited states of even-even nuclei

TABLE VI. Gamma rays observed at the $E_p=729$-kev resonance.

E_γ (Mev) experimental	E_γ (Mev) computed from reference 4	Transition	Intensity number of photons per 100 captures	Anisotropy $\left(\frac{I(0°)-I(90°)}{I(90°)}\right)$
4.23 ±0.10	4.181	(14) → (0)	11±3	−0.42±0.15
3.53 ±0.08	{3.501 {(3.473)	(14) → (1)} ((14) → (2))}	15±3	+0.36±0.15
3.34 ±0.03	3.330	(r) → (8)	62±6	−0.45±0.06
2.94 ±0.06	2.937	(8) → (0)	21±5	
2.26 ±0.03	{2.257 {(2.229)	(8) → (1)} ((8) → (2))}	39±5	
2.06 ±0.04	2.086	(r) → (14)	38±5	−0.28±0.15
1.47 ±0.02	{1.486 {1.451	(8) → (3)} (3) → (0)}	39±8	
1.22 ±0.04	1.244	(14) → (8)	13±4	
0.686±0.006	{(0.708) {0.680	((2) → (0))} (1) → (0)}	39±8	

[13] H. Morinaga and E. Bleuler, Phys. Rev. **103**, 1423 (1956).

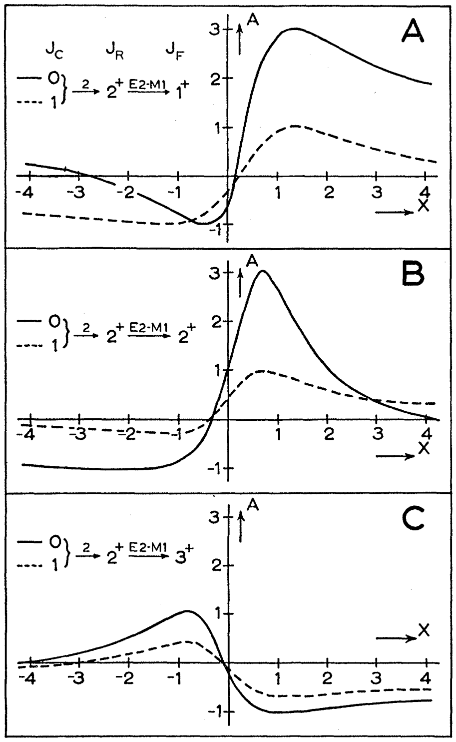

FIG. 3. Theoretical anisotropies calculated as a function of $E2-M1$ mixture of the gamma radiation from a resonance level with spin $J_r=2^+$ to levels with spin $J_f=1^+$, 2^+, or 3^+ (A, B, and C) for d capture and for channel spins $J_c=0$ and 1.

generally have $J=2^+$, the fact that the analogous state in P^{30} (the 2.94-Mev level) has been shown to have $J=2^+$ (Sec. VI d) supports this assumption.

Since shell-model considerations make it probable that all lower levels in P^{30} have positive parity, the fact that only transitions to $T=0$ levels are observed in the decay points to a negative parity of the resonance level and operation of the $E1$ isobaric-spin selection rule. The measured anisotropy ($A=-0.45\pm0.03$) of the ground-state transition then fixes the spin of the resonance level as $J_r=2^-$ (see Table I), since $J_r=0^-$ would give isotropy, while $J_r=1^-$ would lead to $-0.33\leqslant A\leqslant +1.00$. A p-capture resonance with $J_r=2^-$ gives exactly the measured A value. On the basis of a $J_r=2^-$ assignment, the value $A=-0.45\pm0.10$ for the $(r)\rightarrow(2)$ transition uniquely determines the spin of level (2) as $J=1^+$. The measured anisotropy of the 0.708-Mev gamma ray ($A=0.40\pm0.15$) is, within the experimental error, in agreement with the computed value ($A=+0.29$) for a $2^-\rightarrow1^+\rightarrow1^+$ pure dipole cascade (see Table II). The error is too large to determine the intensity of a possible $E2$ admixture for the second gamma ray. The measurement of the anisotropy of the $(r)\rightarrow(3)$ transition is hindered by the weakness of the transition itself, as compared with the Compton ridge of the ground-state transition. The negative anisotropy of the $(3)\rightarrow(0)$ transition, of which the large error is caused by the 1.46-Mev background line from K^{40}, however, suggests a $J=2^+$ assignment for level (3) (see Table II). A possible mixing of gamma-ray multipolarities makes this assignment tentative at most.

The results obtained above are based on the highly probable assumption of a negative parity resonance level. The opposite assumption, however, leads mainly to the same results. The reasoning is somewhat more complicated, since the channel-spin ratio enters into the calculations, and the mixing of $M1$ and $E2$ radiation has to be taken into account. The measured anisotropy of the ground-state transition gives again $J_r=2$, since $J_r=0^+$ would give isotropy just as $J_r=1^+$ with s-capture, while a possible admixture with d-wave protons would result in a positive A. Starting from $J_r=2^+$, level (2) may have $J=0^+$, 1^+, 2^+, 3^+, or 4^+. The value $J=0^+$ can be excluded because it would give isotropy for the $(2)\rightarrow(0)$ transition, whereas $J=4^+$ would lead to a value of A between $+0.17$ and $+0.33$ for the $(r)\rightarrow(2)$ $E2$ transition. The influence of mixing of $M1$ and $E2$ radiation on the anisotropies has been calculated from the tables of Sharp *et al.*[12] for the three remaining possibilities, both for channel spin 0 and 1. The results are presented in Fig. 3 using a mixing parameter $x^2=|S_{E2}|^2/|S_{M1}|^2$, in which S_{E2} and S_{M1} are the matrix elements for electric and magnetic radiation. In the case of $J_f=1^+$ [Fig. 3(A)], the measured anisotropy, $A=-0.45\pm0.10$, for the $(r)\rightarrow(2)$ transition can be effected only with channel-spin mixing without multipolarity mixing; and, even in the extreme case that all transitions proceed through one single channel spin, an $E2$ admixture of at most 1% in intensity explains the observed A. For $J_f=2^+$, however, even for pure $J_c=0$ the high-intensity mixing ratio $I(E2)/I(M1)=0.32$ is needed, while any $J_c=1$ admixture increases the needed radiation mixing ratio appreciably [see Fig. 3(B)]. Thus, $J_f=2^+$ can safely be excluded. From Fig. 3(C), it can be seen that $J_f=3^+$ cannot be excluded. Any value of $I(E2)/I(M1)$ between 0.02 and 0.12 can result in the observed A with a well-chosen channel-spin ratio. Concluding, it can be said that, with the assumed positive-parity resonance level, its spin must be again $J_r=2$, while for the spin of level (2), $J=1^+$ is the most probable value, but $J=3^+$ cannot be excluded. From the decay of the resonance level at $E_p=696$ kev (Sec. VI c), however, the latter value can be definitely ruled out.

Weak gamma rays, other than those mentioned in Table III, may exist. The intense Compton ridges of the high-energy gamma rays prevent the detection of weak low-energy gamma rays. Coincidence measurements point to an $(r)\rightarrow(7)\rightarrow(2)\rightarrow(0)$ cascade, but the resonance is too weak to establish this with certainty.

b. $E_p=414$-kev Resonance

The resonance level decays mainly to the 0.684-Mev level (see Table IV). The fact that 93% of the decay goes to $T=1$ levels can best be explained by assigning $T=0$ and negative parity to the resonance level. The anisotropy of the weak ground-state transition, although it has a large error, then fixes the spin of the resonance level as $J_r=1^-$ (see Table I; $J_r=0^-$ and 2^- can be excluded). The weakness of the ground-state transition can be explained by the fact that electric dipole radiation to the ground state is prohibited by the isobaric-spin selection rule.

The measured anisotropy, $A=-0.22\pm0.04$, of the $(r)\rightarrow(1)$ transition uniquely determines the spin of level (1) as $J=0^+$, because $J=2^+$ would give a lower A for all channel-spin mixings, whereas $J=1^+$ requires a channel-spin ratio different from that calculated from the $(r)\rightarrow(0)$ transition to give the measured A. The spin $J=0^+$ of level (1) was to be expected, since this level is the analog of the Si^{30} ground state. The channel-spin ratio, $t=|S_1|^2/|S_0|^2$, in which S_0 and S_1 are the matrix elements for electric dipole radiation with $J_c=0$ and 1, calculated from the transition to the ground state and the first excited state, is $t=0.5^{+0.7}_{-0.3}$ and $t=0.78\pm0.07$, respectively, in agreement within the experimental errors.

The argumentation given above for the negative parity of the resonance level is strengthened by the fact that an assignment $J_r=0^+$ is impossible as it would give isotropy, whereas $J_r=1^+$ or 2^+ is very improbable, since the first one requires a d-capture resonance competing with s-capture, and the second one requires a high $E2$ admixture to explain the observed anisotropy of the ground-state transition [see Table I and Fig. 3(A)].

Since level (1) has $J=0^+$, isotropy is expected for the $(1)\rightarrow(0)$ transition. However, a small negative anisotropy is measured. The explanation has probably to be found in a weak (not observed) $(2)\rightarrow(0)$ transition. Assuming a direct transition from the resonance level to level (2), taking into account the known channel-spin ratio, a negative A can indeed be expected.

c. Resonance at $E_p=693$ kev

The measured gamma-ray energies and intensities are given in Table V. The most remarkable fact of the decay is (Fig. 6) that only transitions to the seven lowest $T=0$ levels are observed and none to the $T=1$ levels. This fixes the parity of the resonance level as negative and the isobaric spin as $T=1$.

Angular-distribution measurements show weak anisotropies. The complicated character of the spectrum (Fig. 4) prevents a precise measurement of anisotropies. Only to the $(r)\rightarrow(4)$ transition could an anisotropy be assigned. This value, $A=-0.23\pm0.15$, excludes $J_r=0^-$, as this would give isotropy for all gamma rays. From the remaining possibilities, $J_r=1^-$, 2^-, and 3^-, the last two give large anisotropies (see Table I) also if mixture of proton orbital momenta in the first case and channel-spin mixing in the second case are taken into account. Hence, $J_r=1^-$, $T=1$. As to the spins of the levels to which this resonance level decays, it can only be said that $J\geqq3$ can be excluded. In particular, $J=3^+$ (see Sec. VI a) can be excluded for level (2), because otherwise the $M2$ transition $(r)\rightarrow(2)$ would have an intensity comparable to that of the $E1$ transitions, e.g. $(r)\rightarrow(0)$.

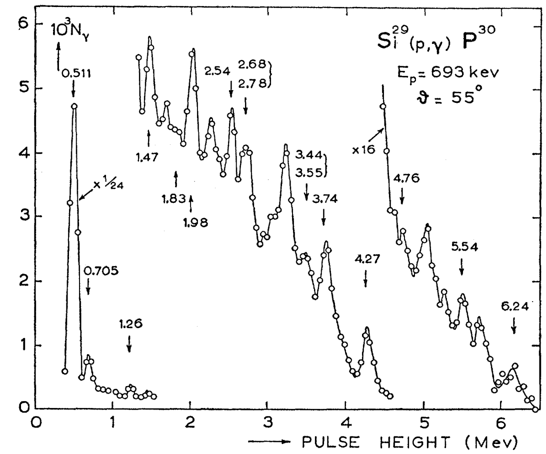

FIG. 4. Scintillation spectrum taken at the 693-kev resonance at 55 degrees to the proton beam. The photopeaks of the fifteen observed gamma rays are indicated by the corresponding energies in Mev.

Coincidence measurements show the 0.706-Mev gamma ray to be in coincidence with $E_\gamma=1.26$ Mev, 1.83 Mev, and 4.26 Mev. Equally, $E_\gamma=4.26$ Mev is in coincidence with $E_\gamma=0.71$-Mev, 1.26-Mev, and 1.97-Mev gamma rays. Branching ratios (see Fig. 6) calculated from this coincidence work are in agreement with the intensities calculated from the analysis of the single spectra.

d. Resonance at $E_p=729$ kev

The measured gamma-ray energies, intensities, and anisotropies are given in Table VI. The high-energy parts of the scintillation spectra taken at zero and 90 degrees to the proton beam with the single gamma rays into which the zero-degree spectrum can be analyzed are shown in Fig. 5.

The decay of the resonance level goes 100% to the $T=1$ levels (8) and (14). Again this has to be explained by assigning a negative parity and $T=0$ to the resonance level. The possibility $J_r=0^-$ can be excluded because it would give isotropic angular distributions. If $J_r=1^-$, the observed anisotropy for the $(r)\rightarrow(8)$ transition can only be explained by assigning $J=0$ to level (8); however, this is impossible, since the observed $(8)\rightarrow(1)$ transition then would be a $(0)\rightarrow(0)$ transition, which is forbidden. Thus, also, $J_r=1^-$ can be excluded. The resonance level, with the remaining possibilities $J_r=2^-$

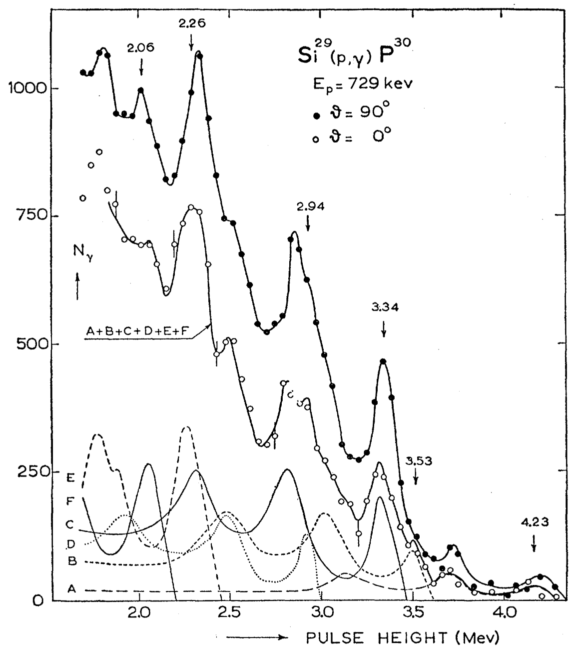

FIG. 5. High-energy part of the scintillation spectra taken at the 729-kev resonance at zero and 90 degrees to the proton beam. The curves A through F show the individual pulse spectra of the six highest energy gamma rays into which the zero-degree spectrum was decomposed.

or 3^-, decays to the levels (8) and (14). These levels both decay to the levels (0) and (1), with spin $J=1^+$ and 0^+, respectively. Therefore, their spin has to be 1^+ or 2^+, since 0^+ drops out as $(0)\rightarrow(0)$ transitions are forbidden, and 3^+ would give octupole radiation. By this reasoning, four possibilities are left for the transitions $(r)\rightarrow(14)$ and $(r)\rightarrow(8)$; these are $2^-\rightarrow 1^+$, $2^-\rightarrow 2^+$, $3^-\rightarrow 1^+$, and $3^-\rightarrow 2^+$. The second one would give positive anisotropy for the transitions under consideration (Table I), in contradiction with the measured values. Computation of the theoretical A for the improbable third case gives $A=+1.00$ and $+0.71$ for $J_c=0$ and 1. Thus, the first and the fourth possibilities remain, both giving an A in agreement with the measured values. The first possibility, however, can be rejected by taking into account the second transition of one of the cascades; $(14)\rightarrow(0)$. On the conditions proposed in this case, the calculated anisotropy for this transition is $A=+0.29$, for pure dipole radiation, whereas the experimental value is $A=-0.42$. A multipolarity mixing $I(E2)/I(M1)=0.60$ is needed to give the measured anisotropy. Moreover, the measured anisotropy of the $(14)\rightarrow(1)$ transition cannot be reached with a reasonable multipolarity mixing, even with an admixture of $(14)\rightarrow(2)$ transition, if $J_r=2^-$. Therefore, the only combination in agreement with the measured A values is the fourth. This fixes the spin of the resonance level as $J_r=3^-$ and that of the levels (8) and (14) both as $J=2^+$. This spin of level (8) was to be expected, since it is the second $T=1$ level and is thus the analog of the first excited state in the even-even nucleus Si^{30}.

The anisotropy of the transition $(14)\rightarrow(0)$, $A=-0.42\pm0.15$, is just between the values calculated for $J_c=0$ and 1 (see Table II). The error in the measured A is too large to calculate the channel-spin ratio. The $E2$ transition $(14)\rightarrow(1)$, with $A=+0.36\pm0.15$, is expected to have an A between $+1.00$ and $+0.78$ for $J_c=0$ and 1, respectively, as multipolarity mixing ($E2$ with $M3$) can be excluded. This discrepancy can be explained by the fact that an admixture of a transition to level (2) cannot be excluded; this lowers the theoretical A (see Table II). A remarkable fact, however, is that the $(14)\rightarrow(1)$ transition with $E2$ character is of higher intensity than the $M1$ transition to level (2). This follows both from the measured gamma-ray energy of the $(1)\rightarrow(0)$ transition and from the anisotropy of the transition mentioned above. Apparently $E2$ transitions between $T=1$ levels are favored.

Two different coincidence measurements have been performed. In the first one, the gate was opened by pulses in a 0.6- to 0.8-Mev channel. From this experiment, the 0.684-Mev gamma ray is proved to be in coincidence with 3.48-, 3.37-, 2.25-, and 2.09-Mev gamma rays, in agreement with the proposed decay scheme. Moreover, a weak 1.00-Mev gamma ray is observed in the coincidence spectrum, possibly originating from a $(8)\rightarrow(4)$ transition.

In the second experiment, the pulses opening the gate were chosen in a 2.4- to 3.6-Mev channel containing contributions from the four highest energy gamma rays of Table VI. The coincidence spectrum shows the six lowest energy gamma rays of Table VI in addition to a weak 1.03-Mev and an unidentified 2.67-Mev gamma ray. The relative intensities calculated from this experiment are, within experimental errors, in agreement with those obtained from the single spectra.

e. Branching Ratios

The results of the present investigation in regard to branching ratios, spins, parities, and isobaric spins are collected in Fig. 6. The branching ratios of those lower levels that decay to more than one other level are given in Table VII. The branching ratios of the resonance levels are already given in Tables III through VI.

TABLE VII. Branching ratios (in percents) of the decay of four P^{30} levels.

From level (Mev) \ To level: (Mev)	2.94	1.96	1.46	0.706	0.684	0
4.18	33	...	...	...	39	28
2.94	...	(2)	24	...	48	26
2.54	...	...	...	13	...	87
1.97	...	...	...	44	...	56

The present results on the $Si^{29}(p,\gamma)P^{30}$ 414-, 696-, and 729-kev resonances can be compared to the data given by Broude *et al.*[2,8] on the same reaction. On the whole, their results are in reasonable agreement with those of the present measurements. However, because their data are preliminary and also because for the interpretation of their measurements they did not yet have available the accurate P^{30} excitation energies obtained from the $S^{32}(d,\alpha)P^{30}$ reaction, it does not seem appropriate to make the comparison between the two sets of results in too much detail.

VII. RADIATION AND PROTON WIDTHS

From the thick-target yield of gamma radiation at a resonance, combined with the decay scheme (as given in Sec. VI) and the measured anisotropies, the number of gamma rays with the resonance level as upper level per incident proton were calculated. This number is proportional to the quantity $(2J_r+1)\Gamma_p\Gamma_\gamma/(\Gamma_p+\Gamma_\gamma)$, where J_r is the spin of the resonance level, Γ_p is the proton width, and Γ_γ is the radiation width of the resonance level summed over all γ transitions de-exciting the level.[11] As the resonance spins are known from the angular-distribution measurements, the quantity $\Gamma_p\Gamma_\gamma/(\Gamma_p+\Gamma_\gamma)$ can be computed directly from the resonance strengths (see Table VIII, column 4). Columns 2 and 3 give the proton orbital momentum l_p, and the spin and parity of the corresponding level as determined in Sec. VI. The proton widths, estimated for p-capture at the first three resonances and for f-capture at the last one, are appreciably larger than the observed values of $\Gamma_p\Gamma_\gamma/(\Gamma_p+\Gamma_\gamma)$. From this fact one may conclude that the values given in column 4 about equal the radiation widths of the corresponding resonance levels.

The resonance strengths given in Table VIII for the three highest resonances can be compared to the values observed by Broude *et al.*[8] They found $(2J_r+1)\Gamma_p\Gamma_\gamma/(\Gamma_p+\Gamma_\gamma)=0.23$, 0.11, and 0.11 ev for the 414-, 696-, and 729-kev resonances, respectively, in good agreement with the present measurements.

VIII. ISOBARIC-SPIN SELECTION RULE

The P^{30} nucleus is one of the self-conjugated nuclei in which $E1$ transitions between levels of the same isobaric spin are prohibited according to the selection rule given by Radicati.[14] The decay of the P^{30} resonance

TABLE VIII. Observed values of $\Gamma_p\Gamma_\gamma/(\Gamma_p+\Gamma_\gamma)$.

E_p (kev)	l_p	J_r	$\Gamma_p\Gamma_\gamma/(\Gamma_p+\Gamma_\gamma)$ (ev) experimental
326	1	2^-	0.014 ± 0.004
414	1	1^-	0.078 ± 0.020
696	1	1^-	0.060 ± 0.015
729	3	3^-	0.021 ± 0.005

[14] L. A. Radicati, Phys. Rev. **87**, 521 (1952).

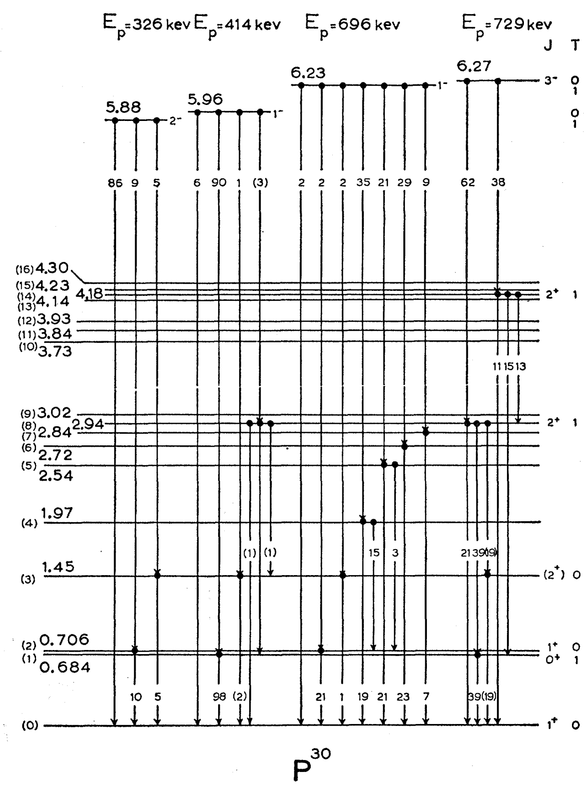

FIG. 6. Level scheme of P^{30}.

levels seems to give both confirmation and violation of this rule.

All theoretical estimates of the unhindered radiation widths give appreciably higher values than the measured ones; an allowance of a factor 2.5 found by Wilkinson[15] for $A<20$ cannot be extrapolated up to $A=30$. Moreover, these estimates do not take into account possible band structure. The existence of rotational levels in this mass region is exhibited clearly by Litherland *et al.*[16] for $A=25$. An attempt has been made by Sheline[17] to classify rotational levels in Al^{28}. Rotational bands in P^{30} cannot be identified with any certainty from the presently available experimental data. One band with levels (1) and (8) and another with levels (0) and (3) as the lowest two levels, which are possible on the ground of the known spins, would give moments of inertia in mutual agreement and in general agreement with those of the neighboring nuclei. This rather tentative assignment of rotational bands is suggested by the relatively strong $E2$ transition $(8)\rightarrow(1)$ in comparison with the competing weaker $M1$ transitions. On the other hand, it should be noted that the relative strength of the $(14)\rightarrow(8)$ and $(14)\rightarrow(1)$ transitions between $T=1$ states is also high.

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[16] Litherland, Paul, Bartholomew, and Gove, Phys. Rev. **102**, 208 (1956).
[17] R. K. Sheline, Nuclear Phys. **2**, 382 (1956–57).

In spite of these objections, a confirmation of the isobaric-spin selection rule can be obtained from the decay of the resonance levels that go predominantly either to $T=0$ or to $T=1$ levels. The $E_p=326$-kev and 696-kev resonances decay 100% to $T=0$ levels; whereas at the $E_p=414$-kev and 723-kev resonances, 93% and 100% of the transitions, respectively, proceed to $T=1$ levels. In general, therefore, T appears to be a fairly good quantum number.

Violation of the selection rule seems to occur at the $E_p=414$-kev resonance, where the isobaric spin forbidden $E1$ transitions $(r)\rightarrow(0)$ and $(r)\rightarrow(3)$ have intensities of about 7% and 1%, respectively, of the allowed $(r)\rightarrow(1)$ transition. Taking into account the relative intensities to be expected according to the E_γ^3 factor for $E1$ transitions of different energies, one can say that the $(r)\rightarrow(0)$ transition has 4% and the $(r)\rightarrow(3)$ transition 2% of the intensity to be expected without operation of the isobaric-spin selection rule. Thus, the transitions have not completely vanished, which can be due to a $T=1$ contamination of the $T=0$ resonance level. This isobaric spin impurity can be caused by Coulomb forces. The influence of the Coulomb perturbation on the isobaric spin mixtures in the ground states of some light nuclei has been calculated by Radicati.[18] These calculations indicate a reduction of the transition probability by the isobaric-spin selection rule by a factor 10^2 to 10^4. As the mixing of isobaric spin states depends on the distance of contaminating states, the mixing will generally be of more importance for higher excited states. A contamination of 2 to 4% (in intensity) with a $T=1$ state for the $J=1^-$, $T=0$, 5.96-Mev level seems very well possible in view of the vicinity of the 6.23-Mev $T=1$ level with the same ordinary spin and parity. Recently, even higher contaminations have been measured.[19]

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[19] D. H. Wilkinson and S. D. Bloom, Phil. Mag. **2**, 63 (1957).