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POLARIZATION OF GAMMA RAYS FROM $Si^{30}(p, \gamma)P^{31}$

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The plane polarization of γ rays from the reaction $Si^{30}(p, \gamma)P^{31}$ is measured using photographic plates impregnated with heavy water, for resonances at $E_p = 1514$, 3308, and 3435 keV. The 8.751-MeV resonance level of P^{31} ($E_p = 1514$ keV) has spin and parity $5/2^+$. The spins of the 10.492-MeV ($E_p = 3308$ keV) and 10.615-MeV ($E_p = 3435$ keV) resonance levels could be $3/2$ and $\geq 5/2$, respectively

1. INTRODUCTION

RESONANCE-level spins and parities of intermediate nuclei formed in reactions with protons can be determined in several ways. The most frequently employed methods require the measurement of p-γ and p-γ-γ correlations, polarization, elastic scattering, and the angular distribution of γ rays accompanying inelastic scattering. These measurements are most easily performed using a spin-zero target nucleus. In this case, when there is no mixture of incident-proton orbital angular momenta and no mixture of initiating channels, the spin and parity of a resonance level can often be determined uniquely.

Radiative capture is the principal process occurring in reactions with protons having energy E_p up to 1 MeV. The spins and parities of resonance levels are then determined by measuring γ angle distributions, γ-γ correlations, and polarization. At higher proton energies elastic and inelastic scattering processes begin to compete. It has been observed that the same resonance levels of an intermediate nucleus sometimes are involved in two processes or in all three of the foregoing processes simultaneously. It then becomes possible to determine the resonance-level spins and parities in different ways. For several reasons the $Si^{30} + p$ reaction is most suitable for these investigations.

The spin and parity characteristics of levels of P^{31} ($J^\pi = 1/2^+$) for $E_p = 3.1$—3.5 MeV were determined by Barnard et al.[1] using measurements of γ angle distributions in inelastic proton scattering by Si^{30} (0^+). They assigned $3/2^-$ to the levels 10.492 ($E_p = 3307$ keV) and 10.615 MeV ($E_p = 3434$ keV).

The elastic scattering of protons by Si^{30} for $E_p = 1$—3.6 MeV has been investigated in [2]. A unique value of J^π was obtained for some P^{31} levels. For the 10.492-MeV ($E_p = 3308$ keV) and 10.615-MeV ($E_p = 3438$ keV) levels observed in the previously mentioned work the assignments were $1/2^+$ and $3/2^+$, respectively.

Although radiative capture is a very weak process at high proton energies, it is of great interest to determine the spins and parities of high-lying levels by measuring γ polarization in transitions to well-investigated low-lying P^{31} levels. In the present work γ polarization was measured for resonances at $E_p = 1514$, 3308, and 3435 keV.

2. EXPERIMENT

The experimental technique has been described in [3,4]. A proton beam accelerated to the resonance energy by the electrostatic generator of the Physico-technical Institute of the Ukrainian Academy of Sciences, was directed against a Si^{30} target. All measurements were obtained using a single target having a thickness corresponding to 3—4 keV losses. Gamma quanta emitted at $\theta = 90°$ impinged normally on photographic plates 200μ thick held together with heavy water in an iron cassette. The plate dimensions were 12×14 mm; the distance from the target was 3.2 cm. The cassette held 24 plates forming two layers, which were irradiated at 10—12°C. The processed plates were scanned with a 630 × binocular microscope; the selected tracks terminated in the emulsion and had dip angles not exceeding 30°. The directions of photoproton tracks in the emulsion plane were measured relative to the proton beam direction (giving the angle α).

The exposure time for resonance at E_p = 1514 keV was 42 hours with a mean current of 4.5 μA at the target. For resonances at 3308 and 3435 keV the plates were irradiated 64 and 16 hours, respectively, with a mean current of about 8 μA. Since the electrostatic generator had not previously been used to accelerate deuterons, the emulsion contained no background of recoil proton tracks representing neutrons from the reaction $D(d, n)He^3$ or other possible reactions with deuterons. In all instances photoproton tracks were observed which corresponded to γ transitions to the ground state and low-lying levels of P^{31}. The mean experimental range of photoprotons for a given γ transition between P^{31} levels was found to agree well with the range determined from the range-energy relation for protons in the impregnated emulsion. This relation was calculated from the composition of the emulsion and the stopping powers of its components by Webb's method.[5] The γ angle distribution for mixed M1 + E2 transitions is given as a function of the mixture coefficient δ by [6]

$$W(\theta) = \sum_{\nu=0,2,\ldots} A_\nu(1) A_\nu(2) P_\nu(\cos\theta), \qquad (1)$$

where θ is the angle between the incident proton and the emitted γ quantum; $A_\nu(1)$ depends on the proton orbital angular momentum, the entrance channel spin, and the resonance level spin; $A_\nu(2)$ is a function depending on the spins of the resonance and low-lying P^{31} level, the γ multipolarity, and δ; $P_\nu(\cos\theta)$ is a Legendre polynomial.

The angular distribution of polarized γ quanta for an M1 + E2 mixture was calculated from [6]

$$W(\theta, \Phi) = W(\theta) + \cos 2\Phi \sum_{\nu=0,2,\ldots} A_\nu(1)\, a_\nu(2)\, P_\nu^{(2)}(\cos\theta), \qquad (2)$$

where θ is the angle between the polarization vector and the reaction plane; $a_\nu(2)$ is a function depending on the same quantities as $A_\nu(2)$; $P_\nu^{(2)}(\cos\theta)$ is an associated Legendre polynomial. The functions $A_\nu(1)$, $A_\nu(2)$, and $a_\nu(2)$ were calculated using coefficients given in [6] and tables in [7].

The photoproton tracks in each group were classified in 30-degree intervals of α: 0–30°, 31–60°, and 61–90°. The ratio W(α = 15°)/W(α = 75°) was compared with calculations from the formula

$$K = [1 + (R-1)\cos^2 15°]/[1 + (R-1)\cos^2 75°], \qquad (3)$$

where R = W(θ = 90°, Φ = 0°)/W(θ = 90°, Φ = 90°) is the intensity ratio between γ rays polarized in the plane of the incident proton and emitted γ quantum, and γ rays polarized perpendicular to this plane. A comparison of the calculated and experimental values of K led to unique values for the P^{31} resonance-level spin and the mixture coefficient δ for E_p = 1514 keV.

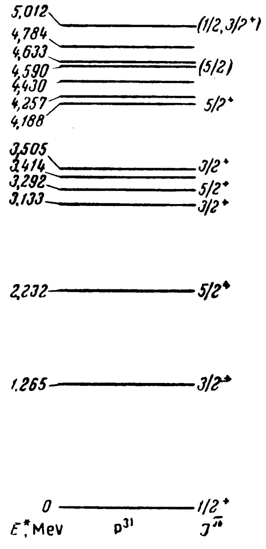

FIG. 1. Scheme of low-lying P^{31} levels.

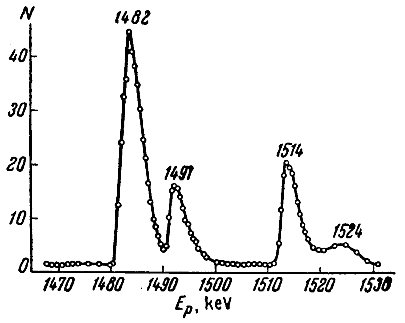

FIG. 2. γ-ray yield from $Si^{30}(p,\gamma)P^{31}$.

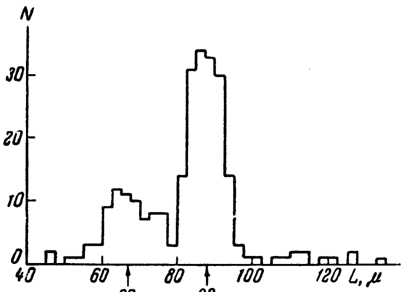

FIG. 3. Photoproton spectrum for resonance at E_p = 1514 keV.

3. RESULTS

The low-lying levels of P^{31} have been investigated thoroughly;[8] their energies, spins, and parities are shown in Fig. 1. The quantum characteristics of resonance levels are determined from the measurements of γ angle distributions, γ-γ correlations, and polarization most frequently by investigating γ transitions to the ground state ($\frac{1}{2}^+$), the first excited state (1.265 MeV, $\frac{3}{2}^+$), and the second excited state (2.232 MeV, $\frac{5}{2}^+$). The relatively large separations of these levels enabled very accurate investigations.

Resonance at E_p = 1514 keV (E^* = 8.751 MeV). Figure 2 shows the γ yield from $Si^{30}(p, \gamma)P^{31}$ in the indicated resonance region. Measurements were performed with a scintillation counter having a NaI(Tl) crystal 40 mm in diameter and 40 mm high in conjunction with an FÉU-1S photomultiplier. The yield curve shows that the target was thin enough to permit good resolution of close-lying resonances.

The measured photoproton spectrum is shown in Fig. 3. Photoprotons with 88 μ mean range correspond to a γ transition to the first excited level; the group with 67 μ mean range corresponds to a transition to the second excited level. The ground-state transition is very weak. The γ angle distribution for a transition from the resonance level to the first excited level was found in [9] to be isotropic. Val'ter et al. therefore concluded that this γ transition can be either of dipole ($\frac{1}{2} \to \frac{3}{2}^+$) or of quadrupole ($\frac{3}{2} \to \frac{3}{2}^+$) type, because calculations indicate an isotropic γ angle distribution for these transitions. However, an isotropic angular distribution in this case does not exclude a possible $\frac{5}{2}^+ \to \frac{3}{2}^+$ transition.

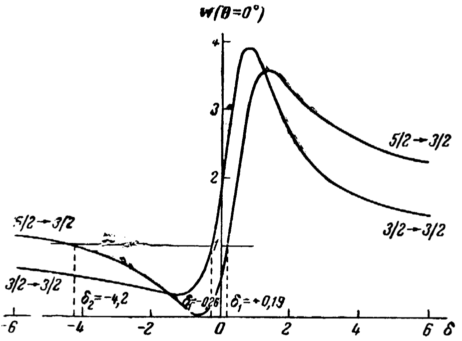

FIG. 4. γ-ray intensity as a function of the mixture coefficient δ for $3/2^+ \to 3/2^+$ and $5/2^+ \to 3/2^+$ transitions.

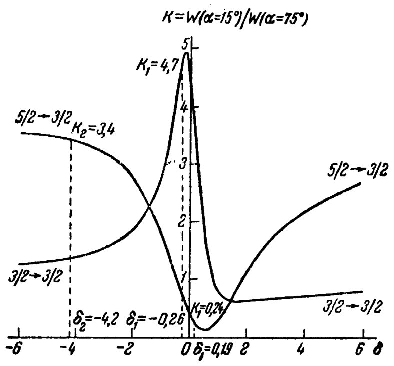

FIG. 5. Ratio between the numbers of photoproton tracks in the ranges α = 0–30° and 61–90° for $3/2^+ \to 3/2^+$ and $5/2^+ \to 3/2^+$ transitions as a function of the mixture coefficient δ. The value K_1 = 0.24 (δ_1 = 0.19, $5/2^+ \to 3/2^+$) is in accord with the observed value K_{exp} = 0.27±0.09.

Figure 4 shows the calculated dependence of γ intensity $W(\theta = 0°)$ on the mixture coefficient δ for $\frac{3}{2}^+ \to \frac{3}{2}^+$ and $\frac{5}{2}^+ \to \frac{3}{2}^+$ transitions. The isotropic γ angle distribution corresponds to $\delta_1 = -0.26$ and $\delta_2 = \infty$ ($\frac{3}{2}^+ \to \frac{3}{2}^+$), and $\delta_1 = 0.19$ and $\delta_2 = -4.2$ ($\frac{5}{2}^+ \to \frac{3}{2}^+$). For a γ transition to the 1.265-MeV level the numbers of photoproton tracks measured in the angle intervals 0–30°, 31–60°, and 61–90° were 22, 51, and 81, respectively, with $K_{exp} = 0.27 \pm 0.09$. It thus follows from the measured γ angle distribution and polarization (Fig. 5) that the 8.75-MeV level of P^{31} has spin $\frac{5}{2}^+$, not $\frac{1}{2}$ or $\frac{3}{2}$, and that the transition is M1 with a small E2 admixture (δ_1 = 0.19). The spin and parity characteristic $\frac{5}{2}^+$ was also obtained in [8] from γ angle distributions and γ-γ correlations.[8] 1)

In the present work resonances were observed at E_p = 1482, 1491, 1514, and 1524 keV in the region of the investigated 1514-keV resonance.

The coincidence, within experimental error, of these resonances with those observed by other investigators confirmed the resonance at E_p = 1514 keV.

Resonances at E_p = 3308 keV (E^* = 10.492 MeV) and E_p = 3435 keV (E^* = 10.615 MeV). Table I gives resonances for E_p = 3.0–3.6 MeV, determined from inelastic γ scattering [1] and elastic proton scattering.[2] The third column gives resonances for E_p = 3.25–3.5 MeV obtained in the present work. The energies obtained for identical resonances observed in the different investigations are in good agreement.

In the present work resonances were established at E_p = 3308 and 3435 keV in a special experiment. These resonances were observed simultaneously in a single target, from both elastic proton scattering and the γ yield.

Figure 6 shows the photoproton spectra for

1)In [2] $1/2^+$ was assigned incorrectly to the 8.751-MeV level (E_p = 1514 keV). Repeated measurements of elastic scattering resonance showed that this assignment should be made to the 8.759-MeV level (E_p = 1524 keV).

Table I. Resonances observed in the $Si^{30} + p$ reaction at E_p = 3.0—3.6 MeV (converted to keV)

E_p [1]	E_p [2]	E_p	E_p [1]	E_p [2]	E_p
3006	3005		3434	3438	3435
3022	3021		3453		3454
3088				3462	
	3118		3467		3470
3154				3496	
3204	3202		3500	3505	3501
3223				3511	
3267		3267	3525		
3307	3308	3308		3535	
3323		3323	3558		
3348	3349	3349	3606		
	3370		3634	3637	
	3389				

Table II. Numbers of photoproton tracks, observed and calculated ranges, and γ transitions for resonance at E_p = 3308 keV

Group	No. of tracks	Range, μ		Transition
		Mean observed	Calculated	
1	45	189	187	10,492 → 0 ($1/2^+$)
2	19	141	140	10,492 → 1,265 ($3/2^+$)
3	35	111	110	10,492 → 2,232 ($5/2^+$)

resonances at 3308 and 3435 keV. The observed photoproton groups with ranges $L > 95\mu$ correspond to γ transitions from resonance levels to the ground and excited 1.265- and 2.232-MeV levels of P^{31}. The production of photoprotons with shorter ranges was associated with γ transitions to close higher-lying levels.

Table II gives the numbers of tracks, the observed and calculated photoproton ranges, and the corresponding γ transitions for three groups in the case of resonance at E_p = 3308 keV. The photoproton tracks were registered on a 40-cm^2 photoplate area.

The assignment $1/2^+$ to the 10.492-MeV resonance level was based on the observed elastic proton scattering.[2] In this case it can be expected that the photoproton angle distributions will be isotropic for all γ transitions. From the measured γ angle distribution for a transition from the first excited 2.23-MeV (2^+) level to the ground state (0^+) of Si^{30} accompanying inelastic scattering we derive the assignment $3/2^-$ for the P^{31} resonance level. For pure dipole (E1) transitions from this level to $1/2^+$, $3/2^+$, and $5/2^+$ levels the coefficients a_2 in the γ angle distribution are -0.6, $+0.75$, and -0.143, respectively. The expected ratios of the numbers of photoproton tracks observed at $\alpha = 0°$ and $90°$, as calculated from the ratio $(1 - a_2)/(1 + a_2)$, would be 4, 0.14, and 1.33 for E1 transitions.

The observed angular distributions of photoprotons are shown in Fig. 7, where they are seen to be anisotropic for transitions to the levels 0 and 1.265 MeV (Fig. 7a, E_p = 3308 keV). It follows from the γ polarization measurements that the 10.492-MeV resonance level cannot have spin and parity $1/2^+$. The photoproton angle distribution associated with the transition to the 1.265-MeV level is biased in the direction opposite to that expected for a $3/2^- \rightarrow 3/2^+$ (E1) transition. The assignment $3/2^+$ must be made to the 10.492-MeV level on the basis of the polarization measurements. The observed anisotropy of the photoproton track distribution for the ground-state transition is smaller than that expected for a $3/2^- \rightarrow 1/2^+$ transition. This may be associated with an M1 + E2 mixture for a $3/2^+ \rightarrow 1/2^+$ transition.

From the γ angle distribution in inelastic scattering we derive the assignment $3/2^-$ for the 10.615-MeV level (E_p = 3435 keV), while from elastic proton scattering we have $3/2^+$.

Figure 6b shows the photoproton spectrum obtained for E_p = 3435 keV. Unlike the preceding case this spectrum contains no transitions to the P^{31} ground state or first excited level. There is one group representing a transition to the second

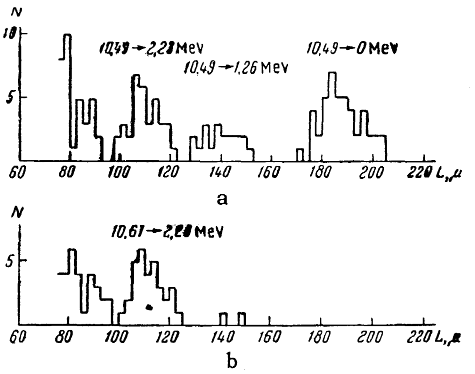

FIG. 6. Photoproton spectrum. a–for resonance at E_p = 3308 keV; b–for resonance at E_p = 3435 keV.

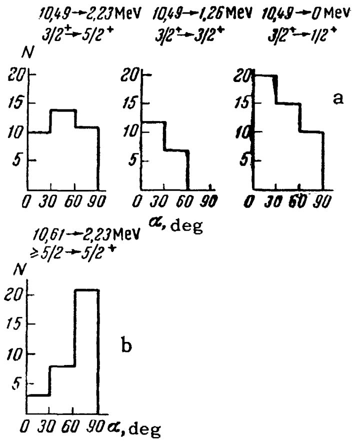

FIG. 7. Angular distributions of photoprotons. a–for resonance at E_p = 3308 keV; b–for resonance at E_p = 3435 keV. The ordinate N is the number of tracks.

excited level at 2.232 MeV (32 tracks registered in a 40-cm^2 area). The photoproton angle distribution (Fig. 7b) is highly asymmetric and differs from the expected nearly isotropic distribution for a $3/2^- \to 5/2^+$ transition. The γ polarization measurements thus do not permit the assignment $3/2^-$ for the 10.615-MeV level. Although a $3/2^+ \to 5/2^+$ transition for certain values of the mixture coefficient δ can lead to the observed photoproton angle distribution, the $3/2^+$ assignment should be excluded because transitions to the ground and 1.265-MeV levels are absent. A spin $\geq 5/2$ must therefore be assigned to the 10.615-MeV resonance level on the basis of the measured photoproton spectrum and γ polarization. The photoproton angle distribution is highly asymmetric and agrees best with $J^\pi = 5/2^-$ or $7/2^+$. The spin and parity could be determined more definitiely through measurement of the 8.38-MeV γ-ray angle distribution in addition.

4. CONCLUSIONS

Resonance at E_p = 1514 keV (E^* = 8.751 MeV). Our measurement of the photoproton angle distribution (for the transition to the 1.265-MeV level) and the γ angle distribution [9] indicate $J^\pi = 5/2^+$ for the 8.751-MeV level of P^{31}. This assignment was also derived from p-γ and p-γ-γ correlation measurements in [8].

Resonances at E_p = 3308 keV (E^* = 10.492 MeV) and E_p = 3435 keV (E^* = 10.615 MeV). Different experimental methods do not yield the same spins and parities for either of the P^{31} resonance levels 10.492 and 10.615 MeV. The measured [1] angular distributions of 2.23-MeV γ rays from inelastic proton scattering by S^{30} for resonances at E_p = 3307 and 3434 keV are $P_0 + (0.244 \pm 0.012) P_2$ and $P_0 + (0.447 \pm 0.011) P_2$ respectively. This suggests $J^\pi = 3/2^-$ for the resonance levels.

The shapes of the resonances of $Si^{30}(p, p)Si^{30}$ for the angles 90°, 125°, and 141° observed in [2] agree well with calculations for resonance at E_p = 3308 keV assuming $l_p = 0$ ($J^\pi = 1/2^+$) and at E_p = 3438 keV with $l_p = 2$ ($J^\pi = 3/2^+, 5/2^+$).

In the present work for resonance at E_p = 3308 keV three photoproton groups were observed corresponding to γ transitions to the levels 0 ($J^\pi = 1/2^+$), 1.265 MeV ($3/2^+$), and 2.232 MeV ($5/2^+$). A spin $\geq 5/2$ for the resonance level appears to be improbable. The observed asymmetry of the photoproton angle distribution for the transition to the 1.265-MeV level is consistent with $J^\pi = 3/2^+$.

For resonance at E_p = 3435 keV only a transition to the second excited level at 2.232 MeV was observed. The high asymmetry of the photoproton angle distribution and the absence of transitions to the ground and 1.265-MeV levels indicate the possibility of $J \geq 5/2$ for the 10.615-MeV level.

The absence of γ angle distribution measurements and the small number of observed photoproton tracks prevent the strict assignments of spins and parities to these levels. Only the most likely assignments can be derived from the given experiments. It is possible that the observed difference between spins and parities obtained from elastic and inelastic scattering and from radiative capture is associated with the existence of close-lying levels having different spins and parities.

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