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PROTONS FROM THE ALPHA-PARTICLE BOMBARDMENT OF ^{31}P

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Synopsis

Resonances in the yield of ground-state protons from alpha-particle bombardment of ^{31}P were investigated in the energy range $E_\alpha = 1.7 - 3.3$ MeV. Fourteen resonances were observed, none of which was known before. Resonance energies and strengths are presented. Angular distribution measurements lead to unique values of the resonance spin in all cases but one. The exception is the strong resonance at $E_\alpha = 3.302$ MeV, which shows a deviation from forward-backward symmetry in the angular distribution, to be explained by assuming interference with some unknown broad resonance(s) with opposite parity, probably at higher energy.

1. *Introduction.* The investigation of resonances in alpha-proton reactions can give information about the resonance levels in the compound nucleus. The yield of such resonances determines a lower limit for the particle widths, whereas the angular distribution in most cases determines the spin of the resonance level, as well as possible mixing parameters in the formation or decay channel. More information about partial width and mixing parameters may be obtained by combining the results of the (α, p) investigation with those of corresponding (p, γ) and (α, γ) experiments.

The following (α, p) reactions in the $Z = 10$—20 region have positive Q value:

$$^{19}\mathrm{F}(\alpha, p)^{22}\mathrm{Ne},\ ^{23}\mathrm{Na}(\alpha, p)^{26}\mathrm{Mg},\ ^{27}\mathrm{Al}(\alpha, p)^{30}\mathrm{Si},\ ^{31}\mathrm{P}(\alpha, p)^{34}\mathrm{S},\ ^{35}\mathrm{Cl}(\alpha, p)^{38}\mathrm{Ar}.$$

In the present experiment the $^{31}\mathrm{P}(\alpha, p)^{34}\mathrm{S}$ reaction was investigated. This reaction is relatively simple, having a target nucleus with ground-state spin $J = \frac{1}{2}$, which eliminates mixing in the formation channel.

Fourteen resonances were observed in the region up to 3.3 MeV alpha-particle energy, none of which was known before neither in this reaction, nor in the corresponding (p, γ) or (α, γ) reaction. In all cases but one, angular distribution measurements agreed well with the theoretical possibilities, leading to unique spin assignments.

Section 2 describes the experimental set-up. The method of analysis and the results are presented in sections 3 and 4, respectively.

2. *Experimental.* Alpha particles accelerated with the Utrecht Van de Graaff generator bombarded targets of zinc phosphide. Targets were prepared by evaporation of Zn_3P_2 onto solid copper backings. Target thicknesses varying from 40 $\mu g/cm^2$ up to 500 $\mu g/cm^2$ were used during the experiment.

The target was surrounded by five silicon surface barrier counters at laboratory angles of 87°, 120°, 135°, 150°, and 172° to the beam. Scattered alpha particles were prevented from reaching the detectors by aluminium foils of 3 mg/cm^2, mounted in front of the detectors. A brief description of the electronic equipment and further data about the experimental set-up have been given in ref. 1.

The energy calibration of the machine was performed with the resonance at 1364.8 keV in the $^{27}Al(p, \alpha)^{24}Mg$ reaction, using the measurement of reference 2, corrected for the new calibration of the 992 keV resonance in the $^{27}Al(p, \gamma)^{28}Si$ reaction [3]).

3. *Analysis.* Yields. From the observed thick target yield at a resonance one easily finds the resonance strength $(2J_r + 1)\Gamma_\alpha\Gamma_p/\Gamma$. When the spin of the resonance level is known, a lower limit for the particle widths can be calculated. Since the Coulomb-barrier penetration is considerably less probable for the incoming alpha particles than for the outgoing protons, the yield of a resonance is mainly determined by the alpha-particle width.

TABLE I

Theoretical $^{31}P(\alpha, p)^{34}S$ angular distribution Legendre polynomial coefficients for different values of the alpha-particle and proton orbital momenta, l_α and l_p, respectively, and for different resonance spins and parities, J^π.

l_α	J^π	l_p	A_0	A_2	A_4	A_6	A_8	A_{10}
0	1/2+	0	1					
1	1/2−	1						
1	3/2−	1	1	1.000				
2	3/2+	2						
2	5/2+	2	1	1.142	0.857			
3	5/2−	3						
3	7/2−	3	1	1.190	1.052	0.758		
4	7/2+	4						
4	9/2+	4	1	1.212	1.133	0.970	0.685	
5	9/2−	5						
5	11/2−	5	1	1.224	1.175	1.070	0.902	0.630

For this reason the lower limit of the proton width is of less interest. Using the lowest possible orbital momentum for the incoming alpha particle one can obtain a lower limit for the dimensionless reduced alpha-particle width θ_α^2.

The necessary penetration factors were calculated using the computer program described in reference 1.

Angular distributions. The ground state of the target nucleus has

$J^\pi = \frac{1}{2}^+$, whereas the ground state of the final nucleus has $J^\pi = 0^+$. The channel spins in both the ingoing and the outgoing channel are thus $J^\pi = \frac{1}{2}^+$, which eliminates the possibility of orbital momentum mixing in either channel. The angular distribution in this reaction then is completely determined by the spin and parity of the resonance level.

However, the angular distribution turns out to be the same for resonances with opposite parity but equal spin value. Table I presents the coefficients in the expected angular distributions for l_α values up to 5.

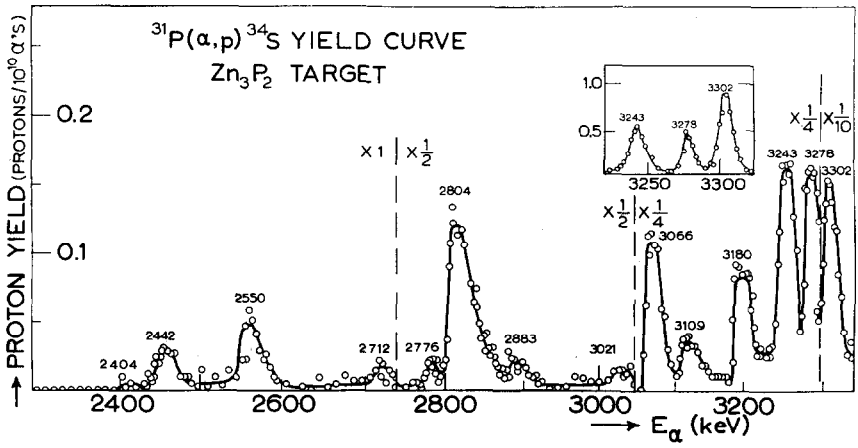

Fig. 1. Yield curve for the ^{31}P(α, p)^{34}S reaction. The plotted number of counts is the sum of the numbers observed at laboratory angles of 87°, 120°, 135°, 150° and 172°. The curve is measured with a 120 μg/cm^2 Zn_3P_2 target. The insert shows the region above 3.2 MeV as measured with a 50 μg/cm^2 Zn_3P_2 target.

After background subtraction the observed angular distributions were converted to the center of mass system and fitted to the theoretical distributions of table I, determining a value of χ^2. Spin values with a χ^2 value above the 0.1% probability limit are supposed to be excluded.

4. *Results*. A yield curve of the ^{31}P(α, p)^{34}S reaction for $E_\alpha = 2.3-3.35$ MeV, showing fourteen resonances, is presented in fig. 1. No resonances were observed in the $E_\alpha = 1.7-2.3$ MeV region. Wigner limit considerations exclude the existence of observable resonances at still lower energies. Each resonance was also established in an angular distribution measurement with a yield that was at least a factor five higher than the off-resonance background.

The angular distributions are shown in fig. 2, together with the theoretically expected curves. The values of χ^2, calculated from the experimental angular distribution for assumed spin values 1/2 through 11/2 for all 14 resonance levels are plotted in fig. 3. A unique spin assignment results in all cases but one.

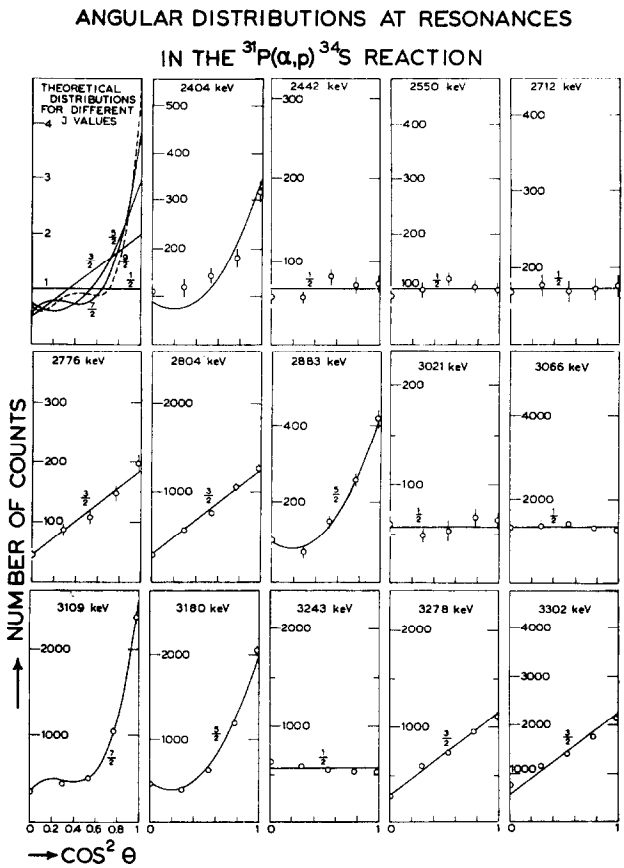

Fig. 2. Angular distributions at fourteen resonances in the $^{31}P(\alpha, p)^{34}S$ reaction with the theoretical possibilities for different spin values.

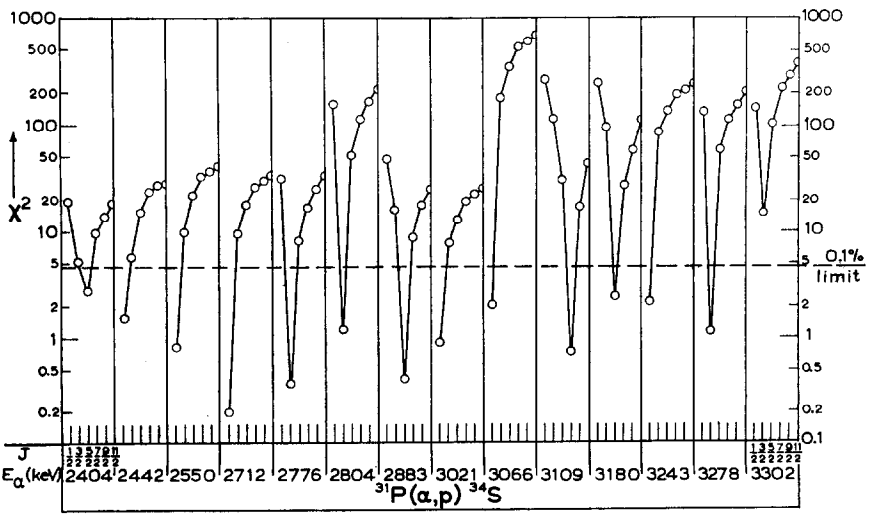

Fig. 3. Angular-distribution χ^2 values for different spins of the resonance level.

Wigner limit reasons exclude the assignment of spin values exceeding 11/2, for any of the observed resonances.

The first three columns of table 2 give the resonance energies, resonance yields and resonance strengths.

The last columns of table II give the value of the resonance spin, a lower limit for the partial α-particle width and a lower limit for the dimensionless reduced α-particle width.

TABLE II

Resonances in the $^{31}P(\alpha, p)^{34}S$ reaction

E_α (keV)	Yield a)	$(2J+1)\,\Gamma_\alpha\Gamma_p/\Gamma$ (eV)	J	Γ_α, Γ_p (eV)	θ_α^2 ($\times 10^2$)
2404 ± 10	0.0017	0.16	5/2	⩾ 0.05	⩾0.6
2442 ± 4	0.023	1.6	1/2	⩾ 0.8	⩾3.2
2550 ± 4	0.034	2.6	1/2	⩾ 1.3	⩾2.0
2712 ± 10	0.0079	0.6	1/2	⩾ 0.30	⩾0.20
2776 ± 4	0.036	2.8	3/2	⩾ 0.7	⩾0.5
2804 ± 2	0.23	18	3/2	⩾ 4.6	⩾2.4
2883 ± 7	0.024	1.9	5/2	⩾ 0.32	⩾0.22
3021 ± 7	0.016	1.1	1/2	⩾ 0.6	⩾0.05
3066 ± 3	0.49	41	1/2	⩾20	⩾1.8
3109 ± 3	0.091	7.6	7/2	⩾ 0.9	⩾0.7
3180 ± 3	0.24	20	5/2	⩾ 3.4	⩾0.7
3243 ± 3	0.54	46	1/2	⩾23	⩾0.9
3278 ± 3	0.44	38	3/2	⩾ 9	⩾0.5
3302 ± 4	0.97	80	(3/2)	⩾21	⩾1.1

a) Yield in protons/10^{10} α particles from a thick Zn_3P_2 target. The experimental error may amount to 20%.

In one case, the strong 3302 keV resonance, no good fit is obtained for any value of the resonance spin. The angular distribution is linear in $\cos^2\theta$, but the measured $P_2(\cos\theta)$ coefficient, $A_2 = 0.74 \pm 0.04$, is appreciably different from the value $A_2 = 1$, expected for $J = 3/2$. For other spin values the fit is still very much worse (see fig. 3). This behaviour can be explained by assuming interference with some unknown broad resonance(s) of opposite parity, probably at higher energy. To test this hypothesis, some measurements were also performed with an additional counter in forward direction ($\theta = 40°$). A significant deviation from symmetry around $\theta = 90°$ was observed, the 40° intensity being higher than that at 140° by a factor 1.16 ± 0.03. The A_2 coefficient has also been measured at energies 1 keV below and 7 and 15 keV above the actual resonance energy, using a 14 keV thick target. No change with energy could be observed, outside the experimental error. This does not invalidate the interference hypothesis, but only shows that the total width of the 3302 keV resonance should be small compared to the 5 keV instrumental resolution.

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