

PROTONS FROM THE ALPHA-PARTICLE BOMBARDMENT OF ^{27}Al

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Synopsis

Energies and strengths are reported of ninety-one $^{27}\text{Al}(\alpha, p)^{30}\text{Si}$ resonances, observed in the energy range $E_\alpha = 1.0\text{--}3.3$ MeV. The natural width of thirteen resonances and the partial widths of one resonance are reported. The observed level density of ^{31}P is in agreement with theory.

Angular distributions of ground-state protons, measured at twenty-six resonances, yield unique spin values for ten levels and the parity of five of these. At twelve resonances the angular distributions exhibit level-interference effects.

1. *Introduction.* The investigation of (α, p) reactions as reported in previous papers^{1) 2)} is continued in the present experiment with the study of the $^{27}\text{Al}(\alpha, p)^{30}\text{Si}$ reaction. The observation of ground-state protons and of protons, decaying to the first excited state of ^{30}Si , gives information about energies, widths, spins and parities of resonance levels in the compound nucleus ^{31}P .

With alpha particle energies up to $E_\alpha = 3.3$ MeV one can excite levels in ^{31}P from $E_x \approx 11$ MeV up to $E_x = 12.5$ MeV. Above $E_x = 11.4$ MeV this region was not investigated earlier. Levels below 11.4 MeV were also observed in a $^{30}\text{Si}(p, \gamma)^{31}\text{P}$ and $^{30}\text{Si}(p, p'\gamma)^{30}\text{Si}$ experiment³⁾. At least ninety-one levels are observed in the present experiment, most of them decaying to the ground state as well as to the first excited state in ^{30}Si .

For a determination of the spin and parity of a resonance level the angular distribution measurement of the ground-state protons is the most suitable. In that case there is no orbital momentum mixing in the outgoing channel. Therefore, as in the case of the $^{23}\text{Na}(\alpha, p)^{26}\text{Mg}$ reaction²⁾, one has to calculate with only one continuous parameter in the angular distribution analysis, if it is assumed that only the two lowest possible orbital momenta contribute in the incoming channel.

Angular distributions were measured at twenty-six resonances, of which fourteen can be treated with a single level analysis. In twelve other cases the angular distribution is certainly distorted by effects of interference between resonance levels.

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

2. *Experimental.* Alpha particles from the Utrecht 3 MV Van de Graaff generator bombarded aluminium targets, evaporated onto a solid copper backing. Target thicknesses of $4.5 \mu\text{g}/\text{cm}^2$ and higher were used.

For the measurement of resonance energies and relative yields one ORTEC surface barrier detector with 300 mm^2 sensitive area was positioned as close to the target as possible at a laboratory angle of $\theta = 120^\circ$ with respect to the incoming beam, detecting about 7% of all emitted protons. Angular distribution measurements were performed with six surface barrier detectors (sensitive area 28 mm^2 , prepared in this laboratory) at angles of $\theta = 172, 150, 135, 120, 105$ and 87 degrees. The investigation of forward-backward symmetry was made with eight of these detectors, positioned at angles of $\theta = 172, 150, 135, 120, 87, 70, 55$ and 40 degrees.

Scattered alpha particles were suppressed by $11 \mu\text{m}$ aluminium foils in front of all detectors. Detector pulses were amplified up to a few volts by a charge sensitive tube preamplifier⁵⁾ and a transistorized RC shaping main amplifier. Each main amplifier leads to a single-channel pulse analyser of which the channel was set with the aid of a multi-channel analyser and a pulse generator.

The energy calibration of the accelerator was performed with the resonance in the $^{27}\text{Al}(p, \alpha)^{24}\text{Mg}$ reaction, which corresponds with the resonance in the $^{27}\text{Al}(p, \gamma)^{28}\text{Si}$ reaction, reported at 1364.8 keV ⁴⁾.

3. *Analysis.* The method of determining resonance strengths, lower limits for particle widths and reduced dimensionless widths was described earlier^{1) 2) 5)}.

In the reaction $^{27}\text{Al}(\alpha, p)^{30}\text{Si}$ the spin of the incoming channel amounts to $5/2$. Thus for most resonances a mixing of three incoming orbital momenta is allowed. For the bombarding energies discussed here, however, the penetration probability for alpha particles with the highest orbital momentum is about one percent of that for alpha particles with the lowest orbital momentum allowed. For this reason only the two lowest orbital momenta of the incoming alpha particles were considered, which makes the analysis analogous to that of the $^{23}\text{Na}(\alpha, p)^{26}\text{Mg}$ reaction. The formula given in ref. 2 for the angular distribution $W(\theta)$ can then be applied, using the theoretical distributions given in table I of the present paper. The whole procedure of center-of-mass corrections, best fit determinations, and error calculus, as well as the method to determine spin and parity possibilities by comparison of χ^2 with the 0.1% probability limit, could thus be taken over for the present experimental data.

TABLE I

Theoretical $^{27}\text{Al}(\alpha, p)^{30}\text{Si}$ 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	l_α'	J^π	l_p	A_0	A_2	A_4	A_6	A_8	A_{10}	A_{12}
3	3	1/2 ⁻	1	1						
2	2	1/2 ⁺	0	1						
1	1	3/2 ⁻	1	1	+0.200					
3	3			1	-0.200					
1	3			0	-0.980					
2	2	3/2 ⁺	2	1	-0.714					
4	4			1	+0.714					
2	4			0	-0.699					
1	1	5/2 ⁻	3	1	-0.914					
3	3			1	-0.038	-0.429				
1	3			0	-0.825	+0.611				
0	0	5/2 ⁺	2	1						
2	2			1	-0.408	+0.551				
0	2			0	-0.107					
1	1	7/2 ⁻	3	1	+0.714					
3	3			1	+0.238	-0.662	+0.758			
1	3			0	-0.540	-0.972				
2	2	7/2 ⁺	4	1	+0.170	-0.980				
4	4			1	+0.436	-0.533	-0.124			
2	4			0	-0.505	-0.698	+0.817			
3	3	9/2 ⁻	5	1	+0.606	-0.421	-0.882			
5	5			1	+0.699	-0.182	-0.597	+0.105		
3	5			0	-0.329	-0.719	-0.426	+0.917		
2	2	9/2 ⁺	4	1	+0.952	+0.429				
4	4			1	+0.590	-0.375	-0.529	+0.872		
2	4			0	-0.321	-0.788	-0.817			
3	3	11/2 ⁻	5	1	+1.061	+0.694	+0.275			
5	5			1	+0.790	-0.013	-0.598	-0.319	+0.935	
3	5			0	-0.212	-0.587	-0.848	-0.685		
4	4	11/2 ⁺	6	1	+0.823	-0.037	-0.674	-0.767		
6	6			1	+0.855	+0.137	-0.486	-0.504	+0.270	
4	6			0	-0.230	-0.593	-0.703	-0.169	+0.065	
5	5	13/2 ⁻	7	1	+0.947	+0.349	-0.329	-0.763	-0.665	
4	4	13/2 ⁺	6	1	+1.119	+0.856	+0.509	+0.189		
6	6			1	+0.912	+0.270	-0.379	-0.616	-0.117	+0.967
4	6			0	-0.150	-0.443	-0.731	-0.830	-0.580	
5	5	15/2 ⁻	7	1	+1.154	+0.959	+0.679	+0.382	+0.135	
6	6	15/2 ⁺	8	1	+1.023	+0.561	-0.027	-0.542	-0.777	-0.579
6	6	17/2 ⁺	8	1	+1.176	+1.028	+0.801	+0.542	+0.293	+0.101

TABLE II

Resonances in the $^{27}\text{Al}(\alpha, p)^{30}\text{Si}$ reaction						
E_α (keV) a)	E_x (MeV)	Γ (keV)	p_0 transition		p_1 transition	
			Yield b)	Strength (eV) c)	Yield b)	Strength (eV) c)
1665	11.114	< 20	0.00052	0.018		
1715	11.158	< 20	0.00048	0.017		
1730	11.171	< 20	0.0014	0.053		
1800	11.232	< 20	0.00073	0.027		
1822	11.251	< 6	0.0049	0.18		
1852	11.277	< 8	0.00093	0.035		
1881	11.302	< 6	0.0019	0.071		
1893	11.313	< 6	0.0089	0.34		
1947	11.360	< 8	0.0028	0.11	0.015	0.59
1988	11.395	< 8	< 0.0008	< 0.03	0.0089	0.35
1999	11.405	< 8	< 0.0008	< 0.03	0.0076	0.30
2012	11.416	< 5	0.00073	0.029	< 0.004	< 0.2
2031	11.433	< 8	< 0.001	< 0.04	0.0088	0.35
2040	11.441	< 8	0.0021	0.085	0.0016	0.066
2065	11.462	< 8	0.00042	0.017	0.0015	0.061
2096	11.498	< 5	0.00042	0.017	0.0094	0.38
2185	11.567	< 8	< 0.002	< 0.07	0.045	1.9
2223	11.600	10 ± 5	0.018	0.77	0.0052	0.22
2273	11.644	< 5	0.0017	0.071	0.014	0.61
2280	11.650	< 5	0.031	1.3	0.014	0.61
2292	11.660	< 5	< 0.0009	< 0.04	0.069	3.0
2320	11.684	< 5	0.037	1.60	0.26	11
2353	11.713	< 5	0.0023	0.10	0.024	1.0
2359	11.718	< 10	< 0.002	< 0.1	0.027	1.2
2370	11.729	< 5	0.024	1.0	0.046	2.0
2398	11.752	< 5	0.0082	0.36	0.0082	0.36
2422	11.773	< 15	0.012	0.52	< 0.005	< 0.2
2434	11.784	< 5	0.0070	0.31	0.089	3.9
2444	11.793	< 5	0.0036	0.16	0.13	5.6
2452	11.799	< 5	0.014	0.60	0.011	0.51
2476	11.820	< 5	0.027	1.2	0.21	9.5
2500	11.841	< 5	0.0093	0.42	0.064	2.9
2517	11.856	8 ± 4	0.028	1.3	0.071	3.2
2529	11.867	< 5	0.065	3.0	0.071	3.2
2536	11.873	< 5	0.075	3.4	0.22	10
2564	11.897	13 ± 5	< 0.004	< 0.2	0.24	1.1
2582	11.913	< 5	0.0092	0.42	0.12	5.3
2598	11.927	< 5	< 0.009	< 0.4	0.10	4.7
2600	11.928	< 5	0.057	2.6	< 0.03	< 1
2611	11.938	< 5	0.0065	0.30	0.15	6.8
2626	11.951	< 10	< 0.005	< 0.2	0.069	3.2
2655	11.976	< 8	0.0051	0.24	0.032	1.5
2679	11.997	< 6	0.024	1.1	0.30	14
2686	12.003	< 5	< 0.004	< 0.2	0.023	1.1
2695	12.011	< 5	< 0.004	< 0.2	0.023	1.1
2705	12.020	< 10	< 0.006	< 0.3	0.077	3.6
2709	12.023	< 8	0.045	2.1	0.26	12
2722	12.035	< 4	0.38	18	0.38	18
2735	12.046	< 5	0.18	8.6	1.24	58
2754	12.063	< 5	< 0.04	< 2	2.28	110
2760	12.068	10 ± 4	0.29	14	1.13	53

TABLE II (continued)

E_α (keV) a)	E_x (MeV)	Γ (keV)	p_0 transition		p_1 transition	
			Yield b)	Strength (eV) c)	Yield b)	Strength (eV) c)
2767	12.074	< 5	0.16	7.7	<0.2	< 9
2783.2	12.088	< 4	0.59	28	0.093	4.4
2797	12.100	< 6	<0.05	< 2	0.28	13
2808	12.110	6 ± 3	0.047	2.2	2.3	110
2822	12.122	< 5	0.210	10	1.0	48
2840	12.137	< 5	0.024	1.1	3.7	18
2851	12.147	< 5	<0.05	< 2	0.16	7.9
2861	12.156	< 5	0.51	24	0.23	11
2870	12.164	4 ± 2	0.59	28	0.37	18
2892	12.183	6 ± 3	<0.05	< 3	0.46	22
2909	12.197	< 5	0.22	10	<0.1	< 7
2916	12.204	< 5	<0.05	< 3	0.28	14
2931.9	12.218	< 5	1.2	56	1.23	60
2949	12.232	< 5	0.45	22	0.38	19
2964	12.245	7 ± 4	<0.03	< 1	0.71	35
2982	12.261	7 ± 4	0.22	11	2.1	101
2995	12.272	<10	0.055	2.7	0.33	16
3013	12.288	<10	0.12	5.7	0.52	25
3015	12.290	< 5	0.12	5.7	0.18	89
3025	12.299	< 8	0.38	19	0.38	19
3033	12.306	< 8	0.38	19	<0.05	< 3
3036	12.308	< 5	<0.07	< 3	0.46	23
3059	12.328	< 5	2.5	120	2.1	100
3085	12.351	<10	0.094	4.7	0.092	4.6
3096	12.360	< 6	<0.1	< 5	0.41	20
3109	12.372	< 5	<0.1	< 7	1.9	95
3120	12.381	< 5	6.6	330	2.8	140
3130	12.390	< 5	1.4	69	2.6	130
3141	12.400	< 5	<0.1	< 5	0.14	7.1
3157	12.414	< 5	1.0	53	4.7	240
3171	12.426	4 ± 2	1.4	72	1.7	85
3176	12.430	< 7	4.7	24	8.3	42
3190	12.442	< 5	2.4	120	8.3	42
3204	12.454	< 5	<0.3	<10	1.7	85
3233	12.480	< 5	0.56	28	3.0	150
3244	12.489	15 ± 4	3.2	163	<0.2	<10
3264	12.507	6 ± 3	0.23	12	4.5	228
3286	12.526	< 5	0.15	7.7	0.57	29
3300	12.538	9 ± 4	<0.1	< 5	1.1	57
3309	12.546	< 5	<0.1	< 5	1.6	81

- a) All energies have an error of ± 4 keV, except the resonances at 2783.2 and at 2931.9 keV of which the error amounts to ± 1.0 keV.
- b) Thick target yield in protons/ 10^{10} alpha particles.
The error may amount up to 20%.
- c) Resonance strength $(2J + 1) \Gamma_\alpha \Gamma_p / \Gamma$.

Interference of resonance levels distorts the angular distributions and may introduce asymmetry around $\theta = 90^\circ$, corresponding with odd terms in the Legendre-polynomial expansion of the angular distribution. Measure-

TABLE II

Results from angular distribution measurements on isolated resonances in the $^{27}\text{Al}(\alpha, p)^{30}\text{Si}$ reaction						
E_α (keV)	Angular distribution (best one-parameter fit)					J^π
	A_2	A_4	A_6	A_8	A_{10}	
1822	$+0.43 \pm 0.16$					$3/2$
1893	$+0.70 \pm 0.04$	-0.02 ± 0.06	$+0.000 \pm 0.001$			$3/2, 7/2^-, 9/2^+$
2223	$+0.44 \pm 0.10$					$3/2$
2280	$+0.89 \pm 0.02$	$+0.33 \pm 0.04$	$+0.09 \pm 0.03$			$7/2^-, 9/2^+$
2370	-0.19 ± 0.04					$3/2$
2598	$+0.54 \pm 0.03$					$3/2$
2679	$+0.70 \pm 0.03$	-0.03 ± 0.05	$+0.000 \pm 0.001$			$3/2, 7/2^-$
2709	-0.63 ± 0.03					$3/2, 5/2^-$
2735	$+0.47 \pm 0.07$					$3/2$
2783	$+0.54 \pm 0.02$	-0.31 ± 0.03	$+0.044 \pm 0.007$			$7/2^-$
2822	$+0.94 \pm 0.03$	$+0.41 \pm 0.07$	-0.02 ± 0.07	$+0.002 \pm 0.009$		$9/2^+$
2909	$+1.054 \pm 0.009$	$+0.68 \pm 0.02$	$+0.26 \pm 0.03$	$+0.006 \pm 0.005$	$+0.05 \pm 0.04$	$11/2^-$
3059	-1.02 ± 0.02	$+0.08 \pm 0.02$				$5/2^-$
3190	$+0.43 \pm 0.02$	-0.49 ± 0.03	$+0.116 \pm 0.011$			$7/2^-$

ments made with detectors in backward as well as in forward directions were analysed in terms of Legendre polynomials, including the odd polynomials. The normal analysis was not applied on angular distributions having coefficients for odd polynomials, significantly different from zero. Alpha-particle energy dependence of the angular distribution is another interference feature which, when observed, makes a single level analysis useless.

4. *Results.* A yield curve for the $^{27}\text{Al}(\alpha, p)^{30}\text{Si}$ reaction in the $E_\alpha = 1.5\text{--}3.3$ MeV region, recorded with one detector at a laboratory angle of $\theta = 120^\circ$, is shown in fig. 1. The ground-state proton (p_0) yield is given

Orbital momentum mixing ratios for the possible J values			$\Gamma_\alpha, \Gamma_{p_0}$ (eV)	θ_α^2 $\times 10^2$
(3/2 ⁻) $+0.18 \pm 0.14$ $+2.0 \pm 0.7$	(3/2 ⁺) $+1.1 \pm 0.3$ -3.6 ± 1.8		≥ 0.045	≥ 3.0
(3/2 ⁻) $+0.6 \pm 0.3$ $+0.9 \pm 0.4$	(3/2 ⁺) $+2.0 \pm 0.4$ $-80 (>10, <-11)$	(7/2 ⁻) -0.01 ± 0.05 (5/2 ⁺) -0.33 ± 0.09	≥ 0.034	≥ 1.1
(3/2 ⁻) $+0.20 \pm 0.10$ $+1.8 \pm 0.4$	(3/2 ⁺) $+1.2 \pm 0.2$ -3.4 ± 1.0		≥ 0.19	≥ 0.49
(7/2 ⁻) $+0.36 \pm 0.08$	(9/2 ⁺) 0.04 ± 0.08		≥ 0.13	≥ 0.21
(3/2 ⁻) -0.31 ± 0.03 $+120 (>25, >-45)$	(3/2 ⁺) $+0.51 \pm 0.03$ -1.14 ± 0.06		≥ 0.25	≥ 0.31
(3/2 ⁻) $+0.36 \pm 0.04$ $+1.27 \pm 0.10$	(3/2 ⁺) $+1.60 \pm 0.09$ -4.5 ± 0.5		≥ 0.65	≥ 0.23
(3/2 ⁻) $+0.7 \pm 0.2$	(3/2 ⁺) $+3.1 \pm 1.1$ $+50 (>6, <-15)$	(7/2 ⁻) -0.02 ± 0.04	≥ 0.14	≥ 0.017
(3/2 ⁻) -1.4 ± 2.3	(3/2 ⁺) $+0.13 \pm 0.03$ -0.50 ± 0.04	(5/2 ⁻) -1.9 ± 0.2	≥ 0.35	≥ 0.13
(3/2 ⁻) $+0.27 \pm 0.09$ $+1.5 \pm 0.3$	(3/2 ⁺) $+1.44 \pm 0.18$ -3.4 ± 0.7		≥ 2.2	≥ 0.30
(7/2 ⁻) -0.25 ± 0.02			≥ 3.5	≥ 0.36
(9/2 ⁺) -0.04 ± 0.11			≥ 1.0	≥ 0.15
(11/2 ⁻) $+0.24 \pm 0.10$			≥ 0.83	≥ 0.67
(5/2 ⁻) -0.13 ± 0.03			≥ 20	≥ 0.49
(7/2 ⁻) -0.43 ± 0.02			≥ 15	≥ 0.40

for the whole energy region, whereas the curve for protons to the first excited state of the final nucleus (p_1) is presented above $E_\alpha = 1.9$ MeV. Below this region pulses from these protons can not be resolved properly from the noise. At least ninety-one resonances are observed, most of them showing the p_0 as well as the p_1 decay. No resonances are observed in the $E_\alpha = 1.0$ – 1.5 MeV region, whereas Wigner limit considerations exclude the existence of observable resonances below $E_\alpha = 1.0$ MeV. Protons deexciting to the second state in ^{30}Si , observed as a third peak in the energy spectrum at backward angles and high alpha particle energies, were not investigated. Table II presents energies, excitation energies ($E_b = 9663.8$ keV⁶), and

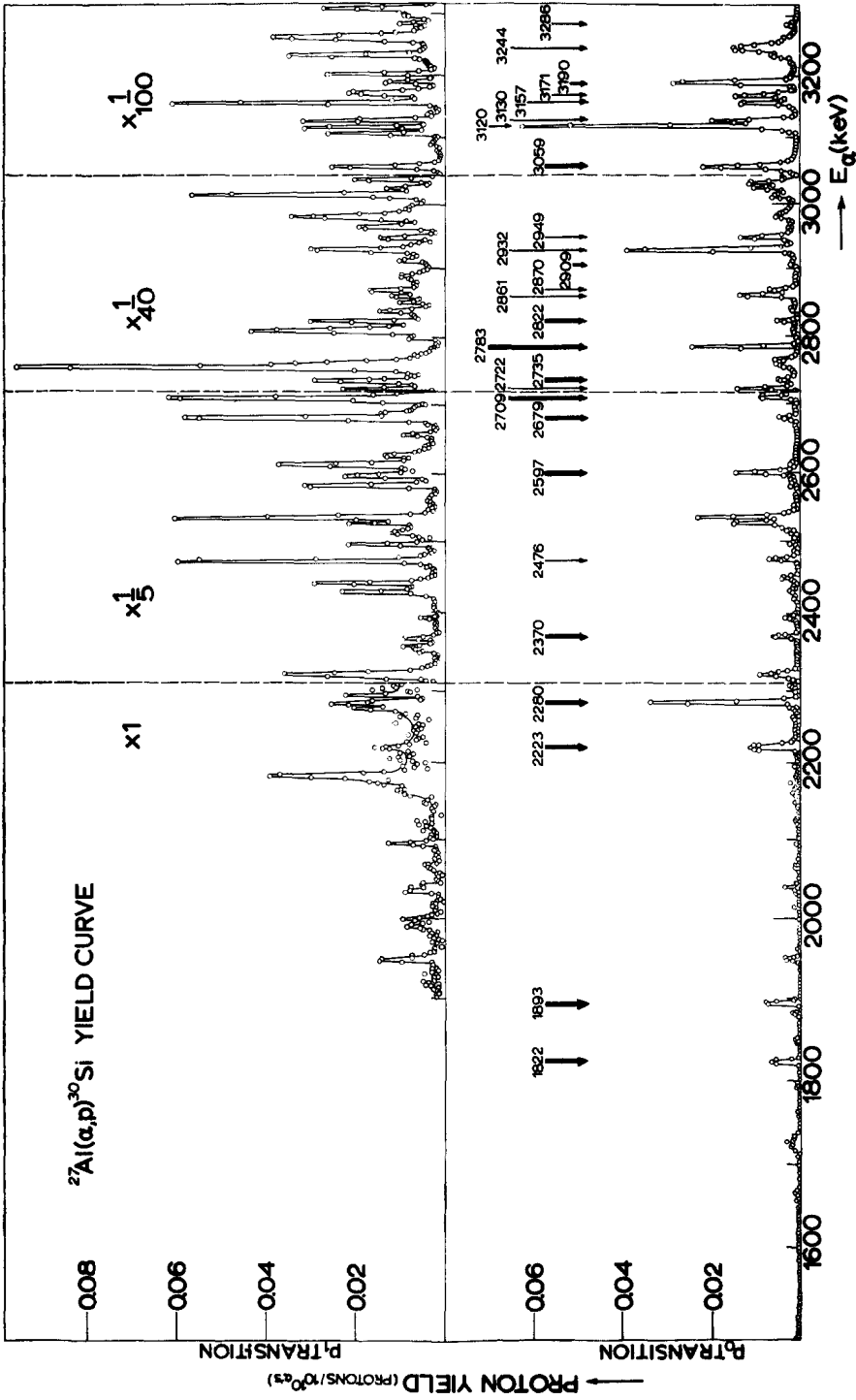


Fig. 1. Yield curve for the $^{27}\text{Al}(\alpha, p)^{30}\text{Si}$ reaction, observed at a laboratory angle $\theta = 120^\circ$. Ground-state proton angular distributions are investigated at resonances indicated with an arrow. Single level analysis was possible at resonances with a thick arrow.

widths, as well as yields and resonance strengths $(2J + 1) \Gamma_\alpha \Gamma_p / \Gamma$ for both proton groups. Ground-state proton yields are corrected for angular distribution effects for the resonances mentioned in tables III and IV.

TABLE IV

Resonances, investigated in the $^{27}\text{Al}(\alpha, p)^{30}\text{Si}$ reaction, which can not be analysed as isolated levels.			
Main even terms in the angular distribution			
E_α	A_2	A_4	A_6
2476	$+0.14 \pm 0.04$	-0.25 ± 0.05	
2722	$+0.21 \pm 0.03$	-0.68 ± 0.04	$+0.13 \pm 0.05$
2861 a)	-0.35 ± 0.03	$+0.13 \pm 0.04$	
2870 a)	$+0.32 \pm 0.05$	-0.73 ± 0.06	$+0.26 \pm 0.07$
2932 b)	$+0.14 \pm 0.04$	$+0.14 \pm 0.04$	
2949 a)	$+0.68 \pm 0.03$	$+0.27 \pm 0.03$	
3120	-1.09 ± 0.01	$+0.29 \pm 0.02$	
3130 a)	$+0.74 \pm 0.06$	-0.37 ± 0.07	
3157 a)b)	-0.12 ± 0.03	-0.41 ± 0.04	
3171 b)	$+0.13 \pm 0.02$	$+0.08 \pm 0.03$	
3244 a)b)	$+0.36 \pm 0.03$	$+0.06 \pm 0.03$	
3286 b)	-0.04 ± 0.04	$+0.16 \pm 0.06$	

- a) The angular distribution is not symmetric around $\theta = 90^\circ$.
 b) The angular distribution shows energy dependence.

Angular distributions were measured at twenty-six of the stronger ground-state proton emitting resonances, sufficiently isolated to try a single level analysis. These resonances are indicated with an arrow in fig. 1. A search for interference effects, such as alpha-particle energy dependence of the angular distribution and deviation from the forward-backward symmetry, was made at those resonances which did satisfy a single level analysis, but which might be influenced by neighbouring resonances. In this way interference effects were demonstrated in twelve cases, whereas the fourteen others, indicated with a thick arrow in fig. 1, could be analysed as single levels. Two examples of angular distributions are shown in fig. 2. The one at $E_\alpha = 2783$ keV, is symmetric around $\theta = 90^\circ$ and the other one at $E_\alpha = 3157$ keV exhibits a strong P_3 component.

The values of χ^2 calculated from the experimental distributions for assumed spin values $\frac{1}{2}$ through $15/2$ or $17/2$ at the fourteen single resonances, are plotted in fig. 3. Wigner limit reasons exclude J^π values not shown in this figure. For the same reason mixing terms, having $l_\alpha \geq 7$ are not taken into account. In cases where χ^2 exceeds the 0.1% probability limit for both parities at a certain J value, only the lowest point has been given.

Table III shows the results from the angular distribution measurements at the single resonances. It presents the Legendre polynomial coefficients of the best one-parameter fit of the observed distribution. Possible solutions for J^π and for the orbital momentum mixing ratio are also given, as well as lower

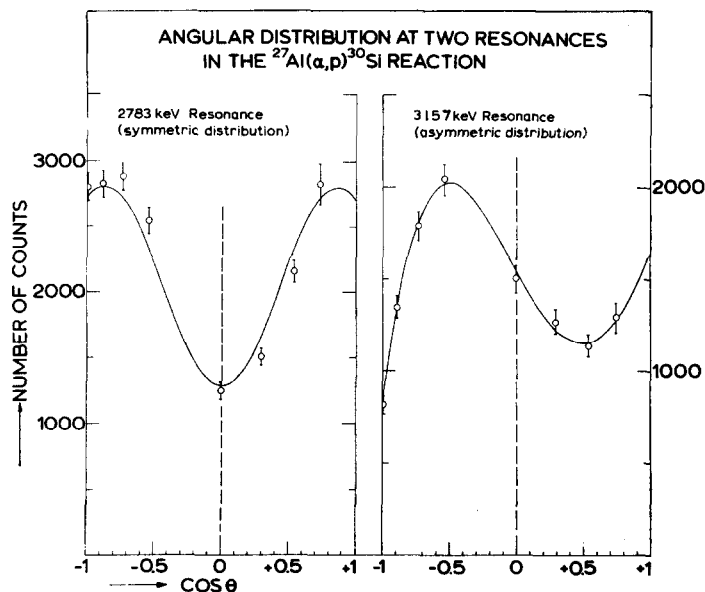


Fig. 2. Ground-state proton angular distributions at two resonances. The resonance at 2783 keV shows symmetry around $\theta = 90^\circ$; the distribution at 3157 keV is asymmetric.

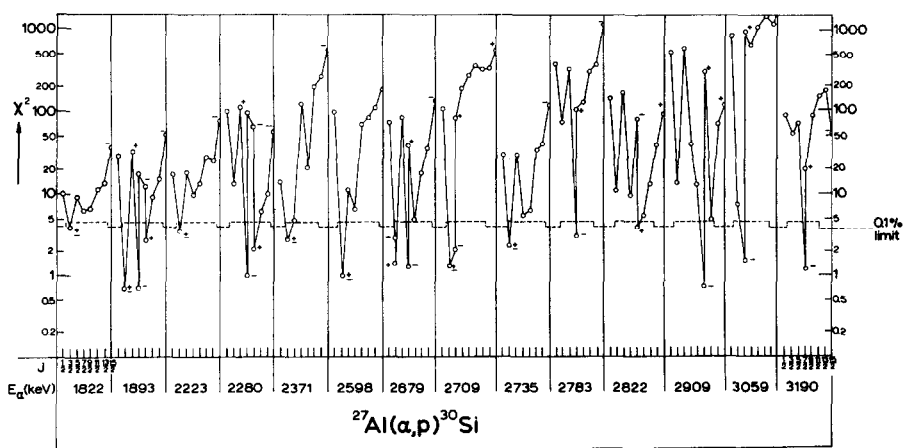


Fig. 3. Angular distribution χ^2 values for different assumed J^π values of the resonance level at fourteen isolated resonances. If for a certain spin value the minimum value of χ^2 exceeds the 0.1% probability limit for both parities, only the lowest of the two values is plotted. At all resonances spin values corresponding to $l_\alpha \leq 5$ are given. At the 2709, 2822, and 2909 keV resonances $l_\alpha = 6$ is also taken into account.

limits for particle widths and dimensionless reduced alpha particle widths θ_α^2 .

The main even terms in the angular distribution of the other twelve resonances, which were investigated, are presented in table IV.

5. *Discussion.* Most levels, investigated in the present experiment have not been observed earlier. The lower part, $E_x = 11.1\text{--}11.4$ MeV, of the region of ^{31}P excitation energy investigated here, overlaps with the energy region covered by Barnard *et al.*³⁾ with the $^{30}\text{Si}(p, \gamma)^{31}\text{P}$ and $^{30}\text{Si}(p, p'\gamma)^{30}\text{Si}$ reactions. The 20 keV error in resonance energies given there makes a comparison of excitation energies of levels in the overlap region rather difficult.

The ratio for the yield Y_p of the p_1 and the p_0 transitions, averaged in a logarithmic way, ($\exp(\ln Y_{p_1}/Y_{p_0})$), over all resonances, decaying in both proton channels, equals 3.1. The yields can be expected to be of the same order. For low values of the resonance spin the penetration probability for ground state protons is higher than for p_1 protons, because of their higher energy. For high spin values however the penetration for p_1 is more probable, the orbital momentum being two units lower than for p_0 protons.

TABLE V

E_x (MeV)	Level densities in ^{31}P	
	Number of levels per MeV	
	Calculated	Observed
9 – 10	23 ($l_p \leq 4$)	34] Barnard <i>et al.</i>
10 – 11	38 ($l_p \leq 5$)	32] Ref. 3.
11.5 – 12.0	60 ($l_\alpha \leq 4$)	56] present
12.0 – 12.5	77 ($l_\alpha \leq 5$)	86] experiment

The relatively high number of levels observed in the present experiment makes a level density consideration possible. The average level spacing in ^{31}P was evaluated as a function of excitation energy, using the formula quoted by Newton⁷⁾. A numerical modification in this expression, as suggested by Preston⁸⁾, was applied, whereas the spin dependence of the average level spacing was taken from ref. 9. The formulae are supposed to be correct within a factor of three. The comparison of the results from calculation and experiment, averaged over two energy regions, is given in table V. In the $E_x = 11.5\text{--}12.0$ MeV region the calculation was performed up to spin values, corresponding to alpha particles having $l_\alpha \leq 4$. For the highest region alpha particles up to $l_\alpha = 5$ are taken into account. The result is rather insensitive to this choice, which was based on the behaviour of the penetration probabilities for alpha particles. The density in two energy ranges observed in the $^{30}\text{Si} + p$ experiment³⁾ is also compared in table V with the densities, calculated for levels which can be excited by protons, having $l_p \leq 4$ and $l_p \leq 5$, respectively. The density formula appears to be in good agreement with both experiments. The average value of the ratio of the calculated density over the observed density amounts to 0.95 for the total number of levels in the four energy regions considered.

The partial widths for a resonance level can be calculated when strength, spin and total width are known, provided that only the alpha particle channel and the two proton channels are open. The resonance at 2223 keV is the only example that can be treated that way, having an observable width $\Gamma = 10 \pm 5$ keV and a spin $J = 3/2$. This resonance level lies far below neutron threshold, whereas the p_2 transition is still negligible because of its negative Q value. Using values of $(2J + 1) \Gamma_\alpha \Gamma_{p_0} / \Gamma = 0.77$ eV and $(2J + 1) \Gamma_\alpha \Gamma_{p_1} / \Gamma = 0.22$ eV as given in table II, the following results are obtained:

$$\Gamma_\alpha = 0.25 \pm 0.05 \text{ eV,}$$

$$\Gamma_{p_0} = 7.8 \pm 3.9 \text{ keV,}$$

$$\Gamma_{p_1} = 2.2 \pm 1.1 \text{ keV.}$$

This solution does not exclude any of the two parity possibilities. In both cases all reduced particle widths are small compared to the Wigner limit. Another solution, giving a very high alpha width can be rejected because of a Wigner limit consideration.

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REFERENCES

- 1) Kuperus, J., *Physica* **30** (1964) 899.
- 2) Kuperus, J., *Physica* **30** (1964) 2253.
- 3) Barnard, A. C. L., Bashkin, S., Broude, C. and Hornback, C. E., *Nuclear Phys.* **23** (1961) 327.
- 4) Borgi, A. W. and Lönsjö, O., Report Fysisk Inst. Oslo Univ. January 1964.
- 5) Kuperus, J., Glaudemans, P. W. M. and Endt, P. M., *Physica* **29** (1963) 1281.
- 6) Endt, P. M. and Van der Leun, C., *Nuclear Phys.* **34** (1962) 1.
- 7) Newton, T. D., *Canad. J. Phys.* **34** (1956) 804.
- 8) Preston, M. A., "Physics of the Nucleus" Addison-Wesley Publ. Cy, Reading (1962) 527.
- 9) Story, J. S., "Nuclear Handbook" ed. O. R. Frisch, G. Newnes Ltd, London (1958) 19-20.