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A STUDY OF THE EXCITED STATES OF ^{31}P WITH THE ^{30}Si(p, γ)^{31}P REACTION

A. C. WOLFF, M. A. MEYER † and P. M. ENDT

Fysisch Laboratorium der Rijksuniversiteit, Utrecht

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Abstract: The γ-ray spectra of 46 resonances in the ^{30}Si(p, γ)^{31}P reaction were measured with a 20 cm^3 Ge(Li) detector. Branching ratios of resonances and bound states were determined. Radioactive sources were used for accurate determination of the energies of the bound states and of the reaction Q-value. The latter, $Q_0 = 7\,297.4 \pm 1.2$ keV, is 10.2 ± 4.0 keV higher than the value from the 1964 mass table. Lifetimes of 13 bound states were obtained from γ-ray Doppler shift measurements. The latter measurements prove that there are two levels at about $E_x = 5.0$ MeV, with excitation energies differing less than 1 keV. They also yield even parity for the $E_x = 4.78$ MeV level.

E | NUCLEAR REACTION ^{30}Si(p, γ), $E = 0.5$-2.3 MeV; measured $\sigma(E; E_\gamma)$, Doppler-shift attenuation. ^{31}P deduced levels, resonance, Q, branchings, $J, \pi, T_{\frac{1}{2}}$. Enriched target.

1. Introduction

The ^{30}Si(p, γ)^{31}P reaction has been extensively investigated in the past; for a review of this work the reader is referred to ref. [1]). Branching ratios of resonances and many bound states were measured, and spins and parities were determined through γ-ray angular-correlation and polarization measurements. All this older work was performed with scintillation counters. The present work was undertaken to see which additional information might be obtained from a re-investigation with a Ge(Li) detector. It was felt that the good energy resolution, an order of magnitude better than that of the NaI counter, should provide at least improved measurements of branching ratios and bound-state excitation energies. In the course of this work it became clear that the information on bound-state lifetimes from Doppler shift measurements is even more useful.

2. Experimental details

This experiment was performed with the proton beam, typically about 5 to 10 μA, from the Utrecht 3 MV Van de Graaff accelerator. The beam was deflected through 90° with an analysing magnet. The magnetic field of the analysing magnet was measured with an NMR fluxmeter. The enriched targets containing 68 % ^{30}Si, 30 % ^{28}Si and 2 % ^{29}Si were obtained from AERE, Harwell. Targets of 15 or 5 μg/cm^2

† On leave from the University of Potchefstroom, South Africa.

cm^2 thickness were used, the latter for measurements on close resonances. A liquid-air cooling trap in front of the water cooled target was used to reduce contaminant deposition.

Gamma-ray spectra were obtained with a Ge(Li) detector, purchased from Princeton Gamma Tech, USA. The detector had an active volume of 20 cm^3. The spectra were spread over about 3000 channels of a 4096-channel LABEN analyser. A typical example of such a spectrum is shown in fig. 1. The resolution was 6 keV at $E_\gamma = 1$ MeV and 18 keV at $E_\gamma = 8$ MeV. With this resolution the Doppler shift of γ-rays emitted by short-lived states could easily be detected. Hence spectra were measured at 90° with respect to the proton beam to determine the energy of the γ-rays. The intensities of the lines were obtained from spectra recorded with the detector placed at an angle of 55° with respect to the proton beam. The efficiency curve of the detector published by Van der Leun *et al.* [2]) was used.

A computer program determined the centre position of the peaks in the pulse-height spectra. With this program, a normalized cross-correlation function of a peak in the spectrum and a Gaussian curve is calculated for different positions of the Gaussian with regard to the peak. This function has a maximum if the peak and the Gaussian coincide. The accuracy of this method varies between 0.1 and 3 keV depending on the strength of the peaks. By changing the width of the Gaussian, the FWHM of the peak is determined in the same way, which provides a check on the possibility that more than one γ-ray contributes. The program also determines the number of pulses in each peak after correcting for the background.

A second computer program determined the energies of the peaks in the pulse-height spectra. The input data for this program are accurately known energies from radioactive sources, distances between full-energy peaks, single- and double-escape peaks, and the requirement that the energies of the γ-rays emitted in cascades should add up to the excitation energy of the resonance state. Peak positions were fitted with a polynomial in the γ-ray energy. Most spectra could well be fitted with a third-degree polynomial, but in some spectra, where very high-energy lines had to be taken into account, a fourth-power term had to be added. Deviations from linearity expressed as the relative difference of the slope of this calibration curve at $E_\gamma = 2$ MeV and at $E_\gamma = 7$ MeV amounted in most of the experiments to about 2 %. Corrections are applied for the recoil energy lost to the residual nucleus upon emission of the γ-quantum and, if necessary, for the Doppler shift due to the motion of the excited nucleus during the emission of the γ-ray.

3. Determination of excitation energies and of the reaction Q-value

The γ-ray spectra of a number of selected resonances were recorded at 90° with respect to the direction of the proton beam in the presence of radioactive sources [3]) such as ^{60}Co, ^{88}Y and ^{24}Na. The distance of these sources from the detector was chosen in such a way that the resulting peaks had about the same number of counts

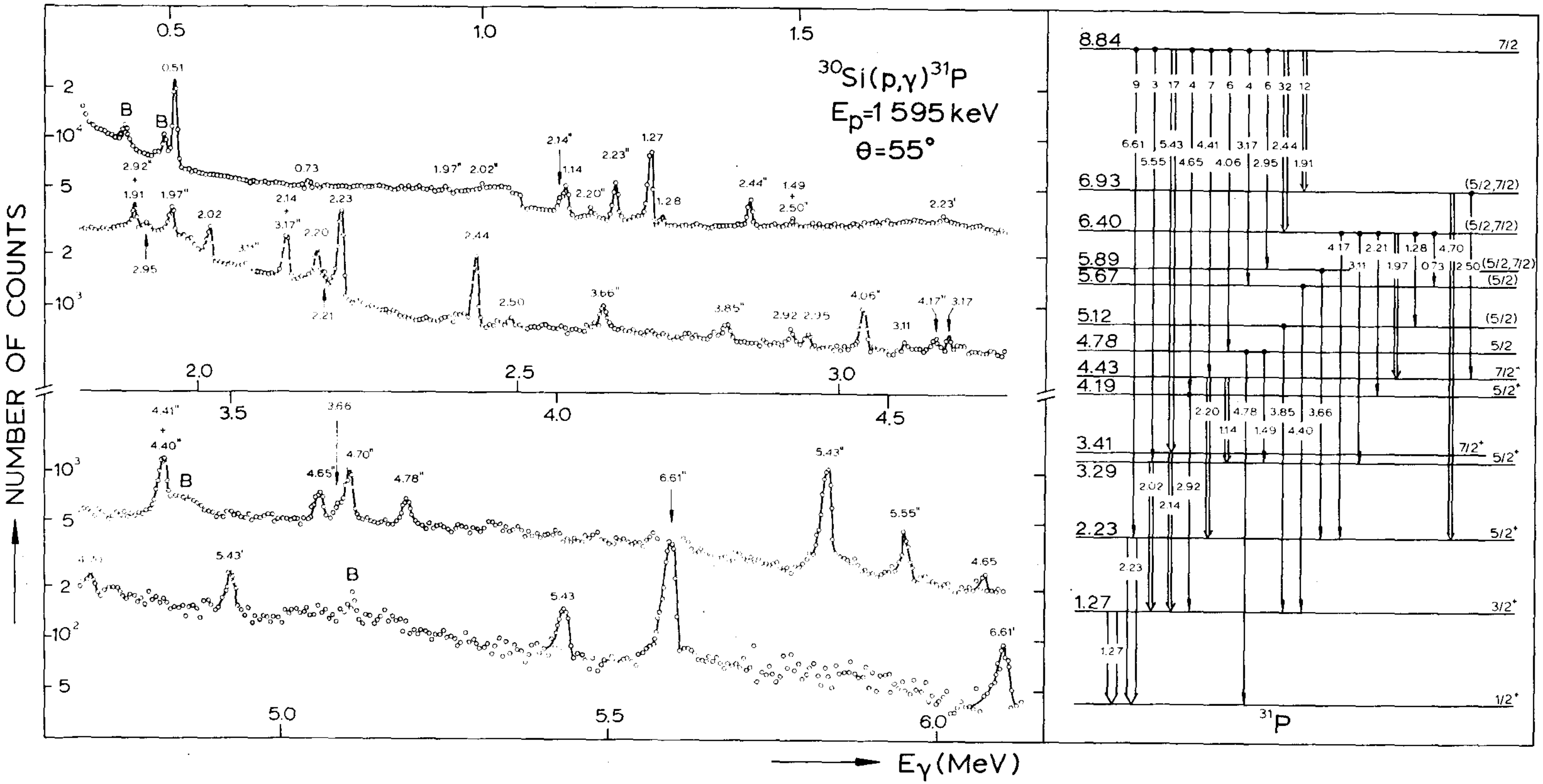

Fig. 1. Gamma-ray spectrum and decay scheme of the $E_p = 1\,595$ keV $^{30}Si(p,\gamma)^{31}P$ resonance measured with a 20 cm³ Ge(Li) detector. In the flat areas between peaks, the average has been plotted of each two consecutive channels. Primes and double primes indicate single- and double-escape peaks, respectively. The resonance decays with strong transitions to relatively high levels.

as other strong peaks in the spectrum. The peaks from the radioactive sources and the peak at 511.006 keV resulting from e^+ annihilation were used for energy calibration. In this way the excitation energies of the levels at 1.27, 2.23, 3.13 and 3.51 MeV were determined. These levels decay to the ground state with the emission of γ-rays for which either the full-energy peaks or the double-escape peaks fall within the range covered by the radioactive sources. The energies of the other levels below 5.1 MeV were then obtained by determining the energies of the γ-rays emitted in the decay of these levels to the levels mentioned above.

The excitation energies of levels above 5.1 MeV can most suitably be found from measurements on low-energy primary transitions exciting these levels, but for this purpose one has to know accurately the resonance excitation energies, which, in turn, can be obtained from the proton resonance energies and the reaction Q-value. The proton resonance energies in the E_p = 0.4-0.9 and 1.0-2.0 MeV regions were accurately (0.6-1.3 keV errors) known from previous work [1]). Those in the E_p = 0.9-1.0 MeV region were determined with comparable accuracy by comparison with the E_p = 991.87 keV ^{27}Al(p, γ)^{28}Si standard resonance [4]). The results are E_p = 942.0, 959.3, 978.2 and 982.5 keV, all $\pm$0.6 keV.

For the Q-value one could, in principle, use the value from the 1964 mass table [5]), Q = 7 287.2$\pm$3.8 keV. It was possible, however, to determine the Q-value more precisely from the present work at resonances showing strong three-step or four-step cascades, in which the relevant peaks of all transitions are found in the region covered with radioactive sources. A good example is the $r \rightarrow 5.02 \rightarrow 1.27 \rightarrow 0$ MeV cascade at the E_p = 1 490 keV resonance. The final result, which is the average of values (in reasonable mutual agreement) obtained at the E_p = 978, 1 289, 1 490, 1 595 and 1 694 keV resonances, is

$$Q = 7\,297.4 \pm 1.2 \text{ keV},$$

i.e. 10.2$\pm$4.0 keV higher than the value from the 1964 mass table. The experimental error given also accounts for the errors in the relevant proton resonance energies.

The ^{31}P excitation energies found from the present work are given in table 1, where they are compared with previous results from the (p, p′), (d, n) and (^{3}He, d) reactions. Especially the (p, p′) results [6]) are in excellent agreement with the present more accurate work; although an error of 5 keV was assigned to all values, the largest deviation amounts to −3.4 keV with an average systematic deviation of only −1.2 keV.

The excitation energies of the E_x = 5 014.9$\pm$1.0 and 5 015.2$\pm$0.8 keV levels were determined at the E_p = 1 289 and 1 490 keV resonances, respectively. That the 5 012$\pm$5 keV level found from the (p, p′) work, which was always thought to be single, actually consists of two separate states, is not proven by the energy difference, which is not significant, but by the fact that the states have different branchings and lifetimes (see below).

Several new levels were found above E_x = 5.1 MeV. Most of these are probably high-spin many-particle states (see sect. 6), which could easily have been missed in the (d, n) and (^{3}He, d) stripping investigations.

TABLE 1
Excitation energies in keV of ^{31}P levels

^{30}Si(p, γ)^{31}P present work [a])	^{31}P(p, p′)^{31}P ref. [6])	^{30}Si(d, n)^{31}P ref. [7])	^{30}Si(^{3}He, d)^{31}P ref. [8])
1 266.13 ±0.12	1 267	1 280±14	1 270
2 233.8 ±0.3	2 234	2 230±10	2 230
3 134.3 ±0.4	3 133	3 100±12	3 140
3 295.0 ±0.2	3 293	3 280±12	3 300
3 414.6 ±0.3	3 414	3 410±20	
3 506.1 ±0.6	3 505	3 490±13	3 520
4 190.9 ±1.0	4 188	4 170±12	4 100
4 260.4 ±1.0	4 257	4 240±12	4 230
4 431.2 ±0.4	4 430	4 430±10	4 450
4 592.5 ±1.0	4 590	4 610±15	4 600
4 634.2 ±0.8	4 633		
4 783.4 ±1.1	4 784	4 780±10	
5 014.9 ±1.0			
5 015.2 ±0.8	5 012	5 010±10	5 030
5 116 ±2	all±5	5 120±10	
5 253 ±2		5 250±10	5 290
5 344 ±2			
5 529 ±2		5 530±10	
5 557 ±2			5 590
5 672.4 ±1.0		5 660±10	
5 773 ±3		5 770±10	
5 892 ±2		5 890±10	
5 988 ±2			
		6 050±10	
(6 103 ±3)		6 180±23(double?)	
(6 232 ±3)		6 240±10	
6 381 ±3		6 380±10	
6 399.0 ±1.0			6 410
6 495 ±3		6 460±10	6 520
6 594 ±2			
6 610 ±2		6 610±10	6 640
6 843 ±2			
(6 908 ±3)			
6 932 ±2			
7 139 ±3		7 150±10	7 150
			all±15

a) Excitation energies in brackets correspond to levels excited at only one resonance.

4. The γ-ray branchings of bound states

The branchings of bound states are shown in table 2. Most values are the average of results obtained at different resonances. At some higher levels, rather large uncertainties remain in the γ-decay. Generally, this was caused by weak excitation of the levels in question, but it also becomes increasingly difficult at higher excitation energies to exclude some modes of de-excitation, which might coincide in energy with known γ-rays in the spectrum.

Bound state E_x (MeV)	J^{π} [a]	Decay to (E_x in ^{31}P in MeV): 0, $\frac{1}{2}^+$	1.27, $\frac{3}{2}^+$	2.23, $\frac{5}{2}^+$	3.29, $\frac{5}{2}^+$	3.41, $\frac{7}{2}^+$	4.19, $\frac{5}{2}^+$	4.43, $\frac{7}{2}^-$	other levels
1.27	$\frac{3}{2}^+$	100							
2.23	$\frac{5}{2}^+$	100							
3.13	$\frac{1}{2}^+$	100							
3.29	$\frac{5}{2}^+$		84±2	16±2					
3.41	$\frac{7}{2}^+$		100						
3.51	$\frac{3}{2}^+$	62±4	38±4	≦ 6					
4.19	$\frac{5}{2}^+$		76±2	24±2					
4.26	$\frac{3}{2}^+$	75±3	25±3						
4.43	$\frac{7}{2}^-$			55±2	41±2	4±1			
4.59	$\frac{3}{2}$*	24±4	54±5	22±6					
4.63	($\frac{5}{2}$, $\frac{7}{2}$)*			25±3	47±5	28±3			
4.78	$\frac{5}{2}^+$*	42±3	12±3	15±3	31±3				
5.01	($\frac{3}{2}$, $\frac{1}{2}$)*	68±3	32±3						
5.02	($\frac{3}{2}$, $\frac{1}{2}$)*	40±3	60±3						
5.12	($\frac{5}{2}$)*		40	20					unknown 40
5.25	$\frac{1}{2}^+$	100							
5.34	(≧$\frac{5}{2}$)*			29±8	21±8	50±10			
5.53	($\frac{5}{2}$)$^+$*			30		35			unknown 35
5.56	($\frac{3}{2}$)*	82±5		18±5					
5.67	($\frac{5}{2}$)*		55	10		10		10	unknown 15
5.77	($\frac{5}{2}$, $\frac{7}{2}$)*			15		20			4.63 25, unknown 40
5.89	($\frac{5}{2}$, $\frac{7}{2}$)*			100					
5.99	($\frac{3}{2}$)*			80±15					5.12 20±15
(6.10)		100							
(6.23)						40			unknown 60
6.38	$\frac{3}{2}^+$, $T = \frac{3}{2}$	18±5		82±5					
6.40	($\frac{5}{2}$, $\frac{7}{2}$)*			2±1	6±2		7±3	75±4	5.12 6±2, 5.67 4±1
6.50	($\frac{1}{2}$, $\frac{3}{2}$)*	60							unknown 40
6.59	($\frac{5}{2}$)*		70						unknown 30
6.61	($\frac{3}{2}$)$^-$*	23±8							4.63 41±9, 5.01 or 5.02 36±9
6.84	($\frac{3}{2}$, $\frac{5}{2}$)*						100		
(6.91)		60							unknown 40
6.93	($\frac{5}{2}$, $\frac{7}{2}$)*			83±6				17±6	
7.14	$\frac{1}{2}^+$, $T = \frac{3}{2}$	100							

Generally, previous work [1]) is in good agreement with the present results, but some levels require special comment.

The 3.51 MeV level decays with a 62 % ground-state transition but also with 1.27 and 2.23 MeV γ-rays which can equally well represent a 3.51 → 1.27 → 0 MeV as a 3.51 → 2.23 → 0 MeV cascade. At all resonances where the 3.51 MeV level is excited, the 1.27 and 2.23 MeV levels are also excited, either directly from the resonance or indirectly through higher levels. An attempt was made by Harris and Breitenbecher [9]) to determine the 3.51 → 1.27 and 3.51 → 2.23 MeV fractions from γ-γ angular-correlation measurements. They concluded that the branching of the 3.51 MeV level to ^{31}P(0), (1) and (2) amounts to 64±3 %, 20±14 %, and 16±14 %, respectively. In the present work, the resolution was good enough to almost separate the 2 234 → 0 MeV tiansition from the 3 506 → 1 266 (E_γ = 2 240 keV) transition, and the 1 266 → 0 MeV transition from a potential 3 506 → 2 234 (E_γ = 1 272 keV) transition. The best spectrum was obtained at the E_p = 1 322 keV resonance, yielding 62±4 %, 38±4 % and < 6 % for the branches to ^{31}P(0), (1) and (2), respectively.

The branching of the 4.59 MeV level was obtained from the resonances at E_p = 1 095 and 1 331 keV. The former resonance was also investigated by Harris and Breitenbecher [9]) with NaI counters. They reported the branching of the 4.63 MeV level and determined its spin as $J = \frac{3}{2}$ from a γ-γ angular correlation measurement. The present work, however, shows that at the E_p = 1 095 keV resonance not the 4.63 MeV level, but the 4.59 MeV level is excited. The branching ratio obtained in ref. [3]) for the 4.63 MeV level agrees with the branching of the 4.59 MeV level as found from the present work. Consequently, the 4.59 MeV level instead of the 4.63 MeV level should have $J = \frac{3}{2}$. In the present experiment, the branching of the 4.63 MeV level was obtained at the E_p = 1 830 keV resonance. The full-energy peak of the 4.63 → 3.41 MeV transition coincides with the double-escape peak of the 2.23 → 0 MeV transition, but the contribution from the latter can easily be subtracted because also the E_γ = 2.23 MeV full-energy peak is observed.

Finally, we discuss the E_x = 5.01-5.02 MeV doublet, already mentioned in sect. 3. The fact that significantly different branchings were obtained for the 5.01 MeV level at different resonances, was the first indication that this state actually is a doublet. At all four resonances where this state is excited with an intensity of at least 10 %, it was found to decay to ^{31}P(0) and (1). At the E_p = 1 289 and 1 301 keV resonances, the branching was measured as 68±3 %, 32±3 % and 68±10 %, 32±10 %, but at the E_p = 1 490 and 1 992 keV resonances 44±3 %, 56±3 % and 38±3 %, 62±3 %, respectively, was obtained. The final proof of the doublet character of the 5.01 MeV level was given from lifetime measurements (see sect. 7).

5. Gamma decay of resonance levels

The high energy resolution together with the accurately known values of the energies of the levels permitted a detailed analysis of the decay of the resonance states.

TABLE 3a

Branching of $^{30}Si(p, \gamma)^{31}P$ resonances (in percent) for $E_p \leqq 1480$ keV

Resonances			Decay to (E_x in ^{31}P in MeV)															
E_p [a] (keV)	E_x (keV)	J^π [a]	0 $\frac{1}{2}^+$	1.27 $\frac{3}{2}^+$	2.23 $\frac{5}{2}^+$	3.13 $\frac{1}{2}^+$	3.29 $\frac{5}{2}^+$	3.41 $\frac{7}{2}^+$	3.51 $\frac{3}{2}^+$	4.19 $\frac{5}{2}^+$	4.26 $\frac{3}{2}^+$	4.43 $\frac{7}{2}^-$	4.59 $\frac{3}{2}$	4.63	4.78 $\frac{5}{2}^+$	5.01 [b]	5.01/5.02 [b]	other levels
499	7 780	$\frac{3}{2}^-$	48	29	6	11					1				3		2	
620	7 898	$\frac{1}{2}$	93	2		1			1								3	
671	7 946	$\frac{3}{2}$	18	20		4	5		16	26			2		9			
760	8 033	$\frac{5}{2}$	2	18	5		4	10	24	28		1		3	5			
777	8 050	$\frac{3}{2}$	68		2	3	2		14	5							3	5.67(3)
835	8 105	$\frac{5}{2}$		65			5		2	11	2				2			5.77(3), 5.99(2), 6.23(8)
942*	8 209	$\frac{3}{2}$	60	24	10		2		2						1			5.25(1)
959*	8 225	$(\frac{5}{2}, \frac{7}{2})$*					50	1		3				3	11			5.12(4), 6.40(26), 6.84(2)
978*	8 244	$(\frac{5}{2})$*		1	1			10		2	1	55					1	5.67(24), 6.84(3), 6.91(2)
983*	8 248	$\frac{3}{2}$	66	4	9	10			1								3	5.25(1), 6.50(1), 6.59(2) [c]
1 095	8 356	$\frac{5}{2}$	1	46			14	1	6		4	2	19		3			6.84(1), 6.93(3)
1 175	8 435	$\frac{7}{2}$			41		33	2		4				4				5.89(2), 6.40(10), 6.59(4)
1 203	8 462	$\frac{5}{2}^{(+)}$		4	25	2	28		13		23		1	4				
1 213	8 471	$\frac{5}{2}$		29			18	3	24	3		4					6	5.67(7), 6.59(4), 6.84(2)
1 289	8 544	$\frac{1}{2}^-$		9		54					1		2			34		
1 298	8 553	$\frac{1}{2}^+$		84	1				6		1						3	5.56(5)
1 301	8 556	$\frac{3}{2}^-$	31	14	25	12			1							12		5.25(5)
1 322	8 576	$\frac{5}{2}^+$		38	10		3	4	27	4	9			2				5.53(3)
1 331	8 585	$\frac{5}{2}$	27	14					13				24				4	6.10(8), 6.61(10)
1 348	8 602	$\frac{5}{2}$			5		10	56				4		10	2			5.89(13)
1 390	8 642	$\frac{5}{2}$		49	20		8	2	5	4		4	3	1				5.12(4)
1 398	8 650	$\frac{3}{2}^{(+)}$	3	73	1	13	3			2	3		1					5.99(1)
1 480	8 730	$\frac{3}{2}^{(+)}$	80	1	8	4	4				1				2			

[a]) From ref. [1]) with additional information (marked with an asterisk) from the present work (see text).
[b]) Numbers in between these two columns indicate that it is uncertain whether the $E_x = 5.01$ or 5.02 MeV level is excited.
[c]) Also to 6.61(2) and 6.84(1).

TABLE 3b

Branching of $^{30}Si(p,\gamma)^{31}P$ resonances (in percent) for $E_p \geqq 1\,482$ keV

Resonances			Decay to (E_x in ^{31}P in MeV)																
E_p [a]) (keV)	E_x (keV)	J^π [a])	0 $\frac{1}{2}^+$	1.27 $\frac{3}{2}^+$	2.23 $\frac{5}{2}^+$	3.13 $\frac{1}{2}^+$	3.29 $\frac{5}{2}^+$	3.41 $\frac{7}{2}^+$	3.51 $\frac{3}{2}^+$	4.19 $\frac{5}{2}^+$	4.26 $\frac{3}{2}^+$	4.43 $\frac{7}{2}^-$	4.59 $\frac{3}{2}$	4.63	4.78 $\frac{5}{2}^+$	5.01 [b])		5.02 [b])	Other levels
1 482	8 731	$\frac{3}{2}$	68	2	14	5	2		2				3				4		
1 490	8 739	$\frac{3}{2}^+$	4	8	9	8	37		2						12			13	5.25(2), 5.56(5)
1 510	8 758	$\frac{5}{2}^+$		55	7			26	1			4	3	1	3				
1 516	8 764	$\frac{1}{2}^+$	84	4		4											8		
1 595	8 841	$\frac{7}{2}$			9		3	17		4		7			6				5.67(4), 5.89(6), 6.40(32) [c])
1 660	8 904	$\frac{1}{2}^+$	2	5	1	38			47				4						5.99(3)
1 667	8 910	$\frac{5}{2}$	2	25	8		3	4	2	3		13		2					5.56(9), 5.67(24), 5.99(2) [d])
1 694	8 936	$\frac{3}{2}^{(+)}$	18	6	35	4	2		4		7				14		2		5.12(7), 7.14(1)
1 746	8 987	$\frac{3}{2}$	60																unknown 40
1 770	9 010	$\frac{5}{2}^+$	11	1	6			3	15	35		3	6	4	1				5.53(6), 5.77(6), 6.38(3)
1 808	9 047	$\frac{3}{2}^-$	90	4		6													
1 815	9 053	($\frac{5}{2}$)*		17	10			24	8	3			9				6		5.67(13), 6.38(7), 6.93(3)
1 830	9 068	$\frac{5}{2}^+$	1	3	37		10	9	1	3		2	2	20	5				5.53(5), 5.99(2)
1 875	9 112	$\frac{7}{2}$			48		7	20		8					8				5.89(9)
1 878	9 114	$\frac{5}{2}^+$			51		5		8	8			9	3	2				5.53(6), 5.56(8)
1 891	9 127	$\frac{5}{2}^+$	7	9	26		6	12	10		4			26					
1 895	9 131	$\frac{5}{2}^+$		36			22				5	21		2	14				
1 918	9 153	$\frac{7}{2}$		7	47			13		14					1				5.34(16), 5.77(2)
1 920	9 155	$\frac{3}{2}^{(+)}$	69	5	11		12										3		
1 941	9 176	$\frac{3}{2}^-$	57	2	13		5						1				8		5.56(1), 5.67(7), 6.61(6)
1 971	9 205	$\frac{7}{2}$		6	7		81												5.12(6)
1 992	9 225	$\frac{1}{2}^-$	10	58		1			6									19	6.50(2), 6.61(2), 7.14(2)
2 187	9 413	$\frac{7}{2}^-$			3			2				88							5.12(2), 5.34(1), 5.67(3) [e])

[a]) From ref. [1]) with additional information (marked with an asterisk) from the present work (see text).
[b]) Numbers in between these two columns indicate that it is uncertain whether the $E_x = 5.01$ or 5.02 MeV level is excited.
[c]) Also to 6.93(12). [d]) Also to 6.59(3). [e]) Also to 5.89(1).

The primary lines are listed in table 3. Levels above 5.1 MeV were considered to be established when the feeding and the decay was seen at at least two resonances. Levels in brackets were excited at only one resonance. No measurements were performed at the weak $E_p = 1\,507$ keV resonance. Resonance excitation energies in table 3 were computed with the Q-value as determined in the present work (see sect. 4).

In general, the agreement between previous [1]) and the present work is quite good. The most obvious differences occur for decays to levels above about 4 MeV, while, in addition, many weak transitions were observed in the present work which were not previously seen in NaI spectra.

6. Spins of bound states and resonances

The spins of most resonance states and of many of the lower bound states are known from previous work. From the present work one can also make good guesses as to the spins of the higher bound states, if one makes the assumption that the stronger transitions are of dipole character. Spins derived in this way are indicated in brackets in table 2. From (d, n) work [7]), a $\frac{3}{2}^-$ state has been found at $E_x = 5\,010 \pm 10$ keV. It is uncertain to which of the doublet components this assignment should be given. The dipole rule limits both spins to $J = (\frac{1}{2}, \frac{3}{2})$.

The resonance spins and parities given in table 3 were mostly taken from ref. [1]). Exceptions are the $E_p = 959$ and 978 keV resonances, where application of the dipole rule helped to further restrict possible spin values, and the $E_p = 1\,815$ keV resonance. The latter was given a $J^\pi = \frac{9}{2}^{(+)}$ assignment in ref. [10]), but the γ-decay, with a strong transition to $^{31}P(1)$ with $J^\pi = \frac{3}{2}^+$, shows that this cannot be true, and that the spin probably is $J = \frac{5}{2}$. The γ-γ angular-correlation measurement [10]), which yielded $J = \frac{9}{2}$, might have been influenced by the fact, that the γ-ray spectrum is more complicated than was thought at the time.

7. Lifetimes of bound states

Gamma-ray Doppler shifts were obtained from spectra taken at $\theta = 0°$ and 140°. For infinitely short-lived states, the shift amounts to $\Delta E_\gamma / E_\gamma = 3.2 \times 10^{-3}$ at $E_p = 1.5$ MeV. The measurements were performed with relatively thick targets (25 and 50 $\mu g/cm^2$) to make sure that the nuclear recoils slowed down all the way in the target layer and not partly in the backing. The measurements at the two angles were alternated in many short (15 min) runs as a precaution against gain drift. The spectra were stored in the two 2048-channel halves of the analyser.

Resonances were selected at which the level in question is strongly excited directly from the resonance. A correction was applied if the level is also excited in a cascade through a higher level with previously measured mean life.

Mean lives were computed from the measured Doppler shifts by applying the slowing-down theory developed by Lindhard [11]) and elaborated by Blaugrund [12]).

The inclusion of atomic-shell effects [13]) in the stopping power leads for the slowing down of ^{31}P ions in Si to a correction of less than 0.5 %. The attenuated Doppler shift F as a fraction of the full shift (as given above) is presented in fig. 2 as a function of the mean life τ_m for two extreme values of the proton energy. The measured shifts and the mean lives computed from them are given in table 4. The errors assigned to the mean lives do not include possible errors in the slowing-down theory. Although the Si-SiO_2 ratio in the target was not accurately known, this has little influence on the mean lives obtained, because the Doppler shift attenuations for Si and SiO_2 are the same within 2 %. Illustrative examples are shown in figs. 3 and 4.

It is seen in table 4 that mean lives obtained from different γ-rays de-exciting the same level agree rather nicely. Also measurements at different resonances show good agreement. And, finally, one finds that for the lowest three levels the present data deviate very little from the averages of previous results [1]), which were mostly obtained from γ-ray resonance fluorescence measurements.

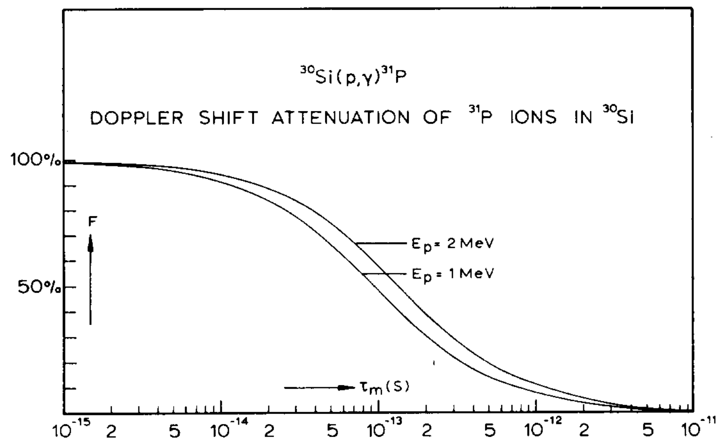

Fig. 2. The Doppler shift F, expressed in percents of the full shift, as a function of the mean life, computed with the theory developed in refs. [11,12]).

Only for the 3.51 MeV level there is a serious disagreement between the $\tau_m = 0.8 \pm 0.3$ fs value obtained by Booth and Wright [15]) from bremsstrahlung resonance fluorescence and the present value of $\tau_m = 13 \pm 7$ fs. It is difficult to judge the reliability of the earlier work because no spectrum of scattered radiation was presented. One might remark, however, that such a short mean life is improbable because it would lead to an E2 contribution in the ground-state transition of 30 W.u. (compare table 5).

The mean lives of the 5.01 and 5.02 MeV levels are seen to differ by almost a factor of 7. For both levels the measured shifts of the γ_0 and γ_1 transitions are in good agreement.

The strengths (in W.u.) of the transitions for which both spin and parity of initial and final state are known, computed [16]) from the mean lives in table 4, are given in table 5.

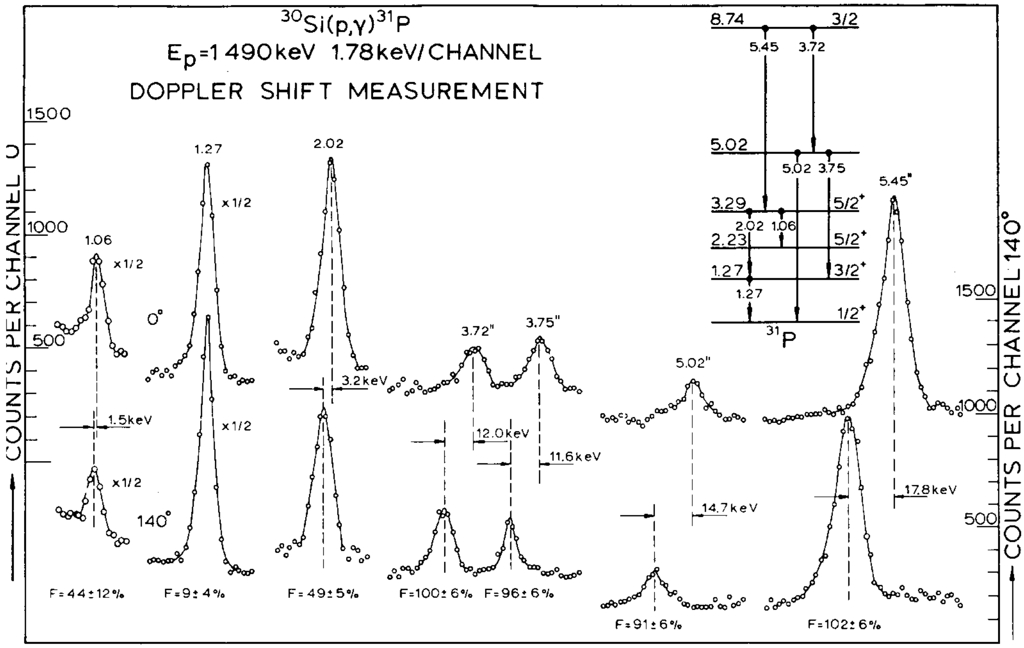

Fig. 3. Doppler shifts of some γ-ray transitions measured at the $E_p = 1\,490$ keV resonance. The primary γ-rays are fully shifted. The shifts of the $E_\gamma = 5.02$ and 3.75 MeV γ-rays are identical within the experimental error; same for the $E_\gamma = 2.02$ and 1.06 MeV γ-rays. The shift of the $E_\gamma = 1.27$ MeV γ-ray as measured at this resonance is unsuitable for a lifetime determination, because the 1.27 MeV level is excited both directly and through several cascades, of which only one is shown in the insert.

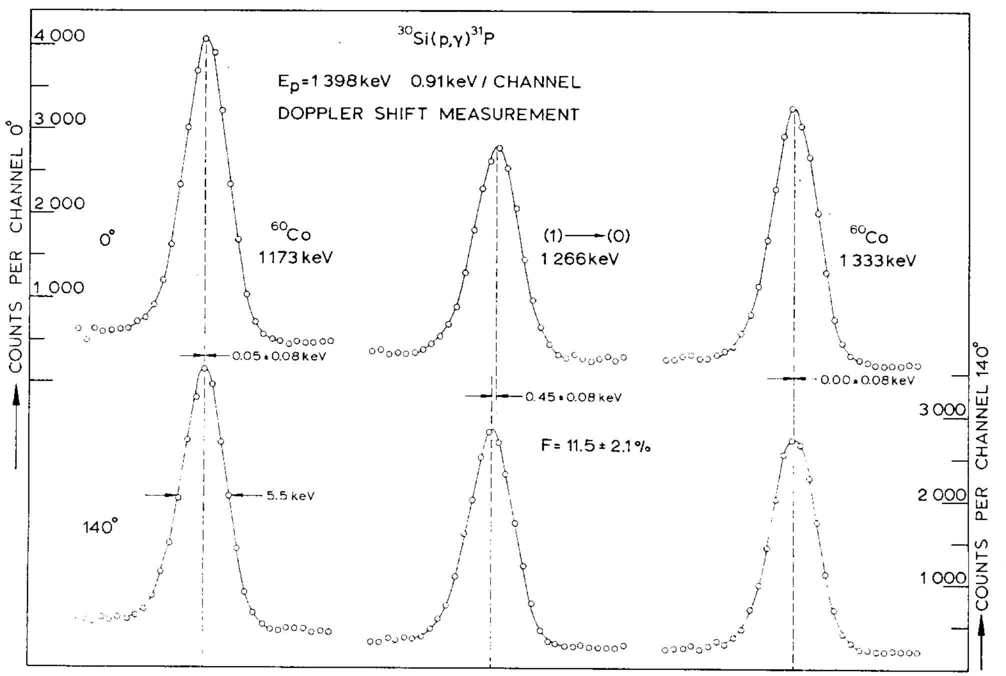

Fig. 4. Doppler shift of the $E_\gamma = 1.27$ MeV transition measured at the $E_p = 1\,398$ keV resonance. The two ^{60}Co γ-rays between which the transition in question is sandwiched, serve to make sure that the two halves of the pulse-height analyser are not shifted respective to one another.

TABLE 4

Lifetime measurements of ^{31}P states

Present experiment						Previous work [c]
E_x (MeV)	E_p (keV)	Decay to (E_x in MeV)	F [a] (%)	τ_m (fs)	$\langle\tau_m\rangle_{av}$ [b] (fs)	τ_m (fs)
1.27	1 398	0	11.5±2.1	770±150	770±150	730±70
2.23	1 694	0	20 ± 2	450± 50	425± 30	440±50
	1 830	0	21 ± 2	420± 50		
	1 878	0	23 ± 2	400± 50		
3.13	1 289	0	95 ± 3	8± 5	8± 4	10± 4
	1 490	0	94 ± 7	10± 10		
3.29	1 203	1.27	42 ± 5	140± 20	135± 14	
		2.23	41 ±20			
	1 490	1.27	48 ± 5	130± 20		
		2.23	44 ±12			
3.41	1 510	1.27	26 ± 4	320± 60	320± 60	
3.51	1 203	0	90 ± 6	15± 9	13± 7	0.8±0.3
	1 770	0	94 ± 6	11± 11		
4.19	1 770	1.27	101 ± 6	< 23	< 23 [b]	
		2.23	88 ±14			
	2 302 [d]	1.27	110 ±11	< 37		
		2.23	81 ±20			
4.26	1 203	0	91 ± 3	13± 5	15± 5	
	1 694	0	85 ± 7	27± 13		
4.43	2 187	2.23	10 ± 4	1 200±500	1 200±500	
		3.29	8 ± 7			
4.59	1 770	1.27	79 ±15	41± 35	44± 19	
	1 878	1.27	77 ±10	46± 23		
4.63	1 830	2.23	48 ±12	100± 30	100± 30	
		3.29	65 ± 9			
4.78	1 694	0	92 ± 6	14± 11	14± 11	
		3.29	91 ±20			
5.01	1 298	0	63 ± 5	67± 11	67± 11	
		1.27	69 ±12			
5.02	1 490	0	91 ± 6	10± 7	10± 7	
		1.27	96 ± 6			

[a]) Some values are the average shifts of the full-energy peak and the double-escape peak.

[b]) The upper limit corresponds to the average measured F-value minus two times the standard deviation.

[c]) As reviewed in ref. [1]).

[d]) The γ-decay measured at this resonance is in general agreement with that given in ref. [14]).

Note added in proof. Recent measurements at the E_p = 1 595 keV resonance yielded mean lives for the 3.41 MeV level and for three levels above E_x = 5.02 MeV. The results are:

E_x (MeV)	Decay to (E_x in MeV)	F (%)	τ_m (fs)
3.41	1.27	34±10	230±100 [a])
5.89	2.23	63±21	80± 60
6.40	4.43	65±11	70± 30
6.93	2.23	97±10	< 40

[a]) Averaging with the value in table 4 yields $\langle\tau_m\rangle_{av}$ = 300±50 fs for the 3.41 MeV level.

TABLE 5

Strengths in Weisskopf units of various transitions in ^{31}P calculated from the branching ratios and lifetimes determined in the present work

E_i (MeV)	E_f (MeV)	$J_i^\pi \rightarrow J_f^\pi$	Mixing ratio	$\lvert M\rvert^2(E1)$ $\times 10^4$	$\lvert M\rvert^2(M1)$ $\times 10^2$	$\lvert M\rvert^2(E2)$
1.27	0	$\frac{3}{2}^+ \rightarrow \frac{1}{2}^+$	0.28 ± 0.02 [a]		1.9	4.2
2.23	0	$\frac{5}{2}^+ \rightarrow \frac{1}{2}^+$				6.0 [b]
3.13	0	$\frac{1}{2}^+ \rightarrow \frac{1}{2}^+$			13	
3.29	1.27	$\frac{5}{2}^+ \rightarrow \frac{3}{2}^+$	-0.37 ± 0.02 [c]		2.1	3.1
3.29	2.23	$\frac{5}{2}^+ \rightarrow \frac{5}{2}^+$	-0.05 ± 0.06 [c,d]		3.0	
3.29	2.23	$\frac{5}{2}^+ \rightarrow \frac{5}{2}^+$	-0.41 ± 0.06 [d,e]		2.6	17
3.41	1.27	$\frac{7}{2}^+ \rightarrow \frac{3}{2}^+$				9.7 [b]
3.51	0	$\frac{3}{2}^+ \rightarrow \frac{1}{2}^+$	-0.41 ± 0.03 [f]		3.1	1.9
4.26	0	$\frac{3}{2}^+ \rightarrow \frac{1}{2}^+$	-0.32 ± 0.04 [f]		1.9	0.5
4.26	1.27	$\frac{3}{2}^+ \rightarrow \frac{3}{2}^+$	-0.25 ± 0.05 [e]		1.9	0.5
4.43	2.23	$\frac{7}{2}^- \rightarrow \frac{5}{2}^+$		0.4 [b]		
4.43	3.29	$\frac{7}{2}^- \rightarrow \frac{5}{2}^+$		2.4 [b]		
4.43	3.41	$\frac{7}{2}^- \rightarrow \frac{7}{2}^+$		0.3 [b]		
4.78 [g]	0	$\frac{5}{2}^+ \rightarrow \frac{1}{2}^+$				1.7 [b]
4.78 [g]	3.29	$\frac{5}{2}^+ \rightarrow \frac{5}{2}^+$	0.05 ± 0.06 [f]		21	

[a]) Ref. [1]).

[b]) It has been assumed that the higher-order magnetic contributions in these transitions are negligible.

[c]) Ref. [17]).

[d]) It is not understood why the mixing ratios given in refs. [17]) and [9]) for this transition differ so much. The value in ref. [17]) might have to be preferred because that in ref. [9]) leads to a very large E2 strength.

[e]) Ref. [9]).

[f]) Ref. [18]).

[g]) See text for a discussion of this level.

Even parity can be assigned to the 4.78 MeV level from the present work, because odd parity would imply an M2 strength for the ground-state transition of 55 W.u. The tentative even-parity assignment given in ref. [18]) was based on insufficient data. Analogous reasoning selects the small value (table 5) of the mixing ratio for the 4.78 → 3.29 MeV transition and rejects the high value (corresponding to almost pure E2 character) which in ref. [18]) could not be excluded as a possibility.

8. Conclusions

The main result of the present investigation might be that it has shown the great versatility for spectroscopic purposes of (p, γ) reactions with Ge(Li) γ-ray detection. The availability of many resonances with greatly different γ-decay makes it possible to investigate almost all lower excited states in contrast to e.g. (d, p) or (d, t) reactions which mainly excite single-particle or hole states, respectively. Excitation energies and Q-values can be measured with a precision surpassing by an order of magnitude that to be obtained from such charged-particle reactions. Gamma-ray branchings of resonances and bound states can be determined faster and in more detail than from

NaI work even without time-consuming measurements of coincidence spectra. Although the Doppler shifts produced by the capture of such a light particle as a proton at energies only up to $E_p = 2$ MeV are quite small, they provide a wealth of extremely useful information on the mean lives of bound states. It is amazing to see (compare table 4) that almost all mean lives of ^{31}P bound states up to $E_x = 5.1$ MeV correspond to shifts in the useful region of between 10 % and 90 % of the full shift for infinitely short-lived states. In the present work the measured mean lives helped to restrict the possibilities for spins and parities of bound states and provided a definite proof of the existence of a doublet of levels in ^{31}P at $E_x = 5.01$ and 5.02 MeV.

In the present paper we shall refrain from comparing the experimental information obtained with any nuclear model. Such calculations starting from the shell model with a two-body surface-delta interaction are in progress.

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