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SPIN DETERMINATIONS OF ^{31}P LEVELS FROM THE ^{30}Si(p, γ) REACTION

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Abstract: The angular distributions of primary and secondary γ-ray transitions at seven resonances in the ^{30}Si(p, γ)^{31}P reaction were measured with a 30 cm^3 Ge(Li) detector. The strengths of the resonances between 800 and 1000 keV and the strength of the $E_p = 2187$ keV resonance were determined. The mean lifetime τ_m (or upper limits) for the ^{31}P 5.53, 5.56 and 5.67 MeV levels was obtained from γ-ray Doppler shift measurements as <37, <25 and 45 ± 20 fs, respectively. The measurements lead to the following J^π assignments of ^{31}P bound states and resonance levels: $J^\pi(4.63) = \frac{7}{2}^+$ $(\frac{5}{2}^+)$, $J^\pi(5.01) = \frac{3}{2}$ $(\frac{1}{2}^-)$, $J^\pi(5.02) = \frac{1}{2}$ $(\frac{3}{2}^+)$, $J^\pi(5.53) = \frac{7}{2}$ $(\frac{5}{2}^+)$, $J(5.56) = \frac{3}{2}$, $J(5.67) = \frac{5}{2}$, $J(6.40) = \frac{7}{2}$, $J(6.93) = (\frac{5}{2}, \frac{7}{2})$, $J(8.22) = \frac{7}{2}$ and $J^\pi(8.23) = \frac{5}{2}^-$. There are strong arguments which allow to identify the 5.01 and 5.67 MeV levels with the $2p_{\frac{3}{2}}$ and $1f_{\frac{5}{2}}$ single-particle states, respectively.

The even-parity states in ^{31}P up to 5.8 MeV are compared with recent many-particle shell-model calculations.

E | NUCLEAR REACTIONS ^{30}Si(p, γ), $E = 0.8$–1.0, 2.187 MeV; measured $\sigma(E)$. ^{30}Si(p, γ), $E = 0.959$–1.830; measured $\sigma(E; E_\gamma, \theta)$. Doppler-shift attenuation. ^{31}P resonances deduced strength, J, π. ^{31}P levels deduced $T_{\frac{1}{2}}$, J, π. Enriched targets.

1. Introduction

Spins and parities of ^{31}P levels excited in the ^{30}Si(p, γ)^{31}P reaction have been investigated in the past by Harris *et al.* [1-3]) and Van Rinsvelt *et al.* [4-6]). A review of this work and of older work is given in ref. [7]). Recently Bornmann *et al.* [8]) and Wiechers *et al.* [9]) studied spins of resonance levels above $E_p = 2$ MeV. The angular distribution and correlation measurements in all these measurements were performed with NaI(Tl) detectors.

In a previous paper [10]), the decay of ^{31}P levels was investigated with a Ge(Li) detector. The good energy resolution of this detector made it possible to study the γ-decay of high-energy bound states and to obtain lifetimes of most bound states from γ-ray Doppler shift attenuation measurements. In the present investigation, angular distributions of primary transitions to and secondary transitions from bound states above 4.5 MeV were measured at seven resonances with a Ge(Li) detector. Some additional information was obtained on resonance strengths and on the lifetimes of three bound states. From these data, the spins and parities of several ^{31}P levels could be determined.

2. Experimental details

This experiment was carried out with the Utrecht 3 MV Van de Graaff accelerator. Details of the experimental set-up have been described previously [4,10]. The ^{30}Si targets were enriched to 68 %.

The angular distribution measurements were performed with a 30 cm^3 Ge(Li) detector positioned at 0°, 35°, 55° and 90° with respect to the proton beam. The front face of the detector was 4 cm from the target. Each of the four spectra was recorded in a 1024-channel section of a 4096-channel LABEN analyser. Every 15 min the detector was moved to another angle as a precaution against target deterioration and gain drift of the electronics. The eccentricity of the target spot was measured at the isotropic $E_p = 620$ keV $^{30}Si(p, \gamma)^{31}P$ resonance. Corrections were applied for this eccentricity and for differences in γ-ray absorption of the target holder at the four angles. The values of the solid-angle attenuation factors used in the calculations were $Q_2 = 0.90$ and $Q_4 = 0.70$. These values are equal to those for a NaI detector for the same solid angle.

3. Analysis of the data

The angular distribution measurements are analysed in terms of Legendre polynomials of even order. It is assumed that octupole radiation can be neglected. Since the target nucleus has zero spin, the theoretical coefficients of primary transitions between states with given J are only functions of the quadrupole/dipole mixing ratio x. For any possible combination of initial- and final-state spins (J_r, J) and for different values of x, one then calculates $Q^2 = \sum_i W_i(N_i^{exp} - N_i^{theor})^2/(N-M)$, where i labels the angles. The N_i^{exp} are the number of counts at the angle i, and $N_i^{theor} = C\{1+a_2(x)Q_2P_2(\cos\theta_i)+a_4(x)Q_4P_4(\cos\theta_i)\}$ indicates the "theoretical number of counts". The weighting factors W_i are equal to the inverse squared error in N_i^{exp} (in which background subtraction has been taken into account), and the number of free parameters $N-M = 2$ in the present case, where there are four angles and two parameters $(C$ and $x)$ to be fitted (but $N-M = 3$ for a pure quadrupole transition). The $a_2(x)$ and $a_4(x)$ can be found in tables, e.g. in those given by Smith [11]. An example of a $Q^2(x)$ plot, in which the computer minimization with respect to C has already been performed, is given in fig. 1. A second part of the program [12] determines the best value of x and its error. If $\chi^2 = Q^2_{min}$ is larger than unity, the error in x is multiplied by $\sqrt{\chi^2}$. In fig. 1 the 0.1 % probability limit is indicated which separates the acceptable from the unacceptable solutions (J_r, J, x).

To further reduce the number of remaining solutions, the quadrupole strengths of primary transitions are computed for each solution. They are found from the resonance strengths $(2J_r+1)\Gamma_p\Gamma_\gamma/\Gamma$ as measured by Van Rinsvelt [4,5] and in the present work (table 1). At the $E_p = 1301$, 1490 and 1830 keV resonances, it is known that $\Gamma \approx \Gamma_p \gg \Gamma_\gamma$ such that Γ_γ can be obtained directly. At the other resonances, the same assumption yields a lower limit for Γ_γ. Solutions implying E2 or M2 strengths above

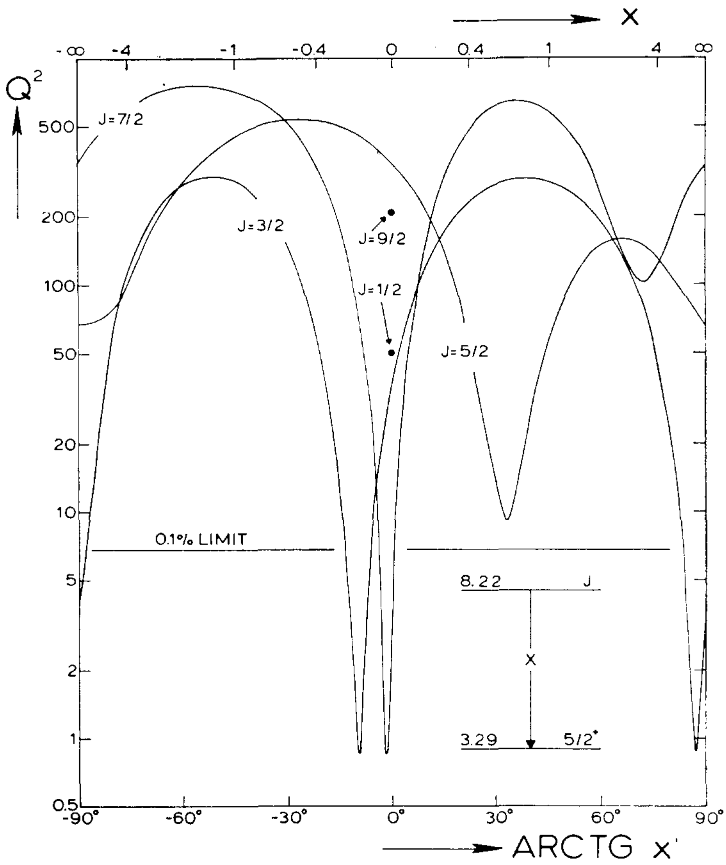

Fig. 1. A plot of Q^2 as a function of the mixing ratio x for the r → 3.29 MeV transition at the E_p = 959 keV resonance with the resonance spin as a parameter.

TABLE 1

Strength of $^{30}Si(p,\gamma)^{31}P$ resonances as measured in this work

E_p [a] (keV)	$(2J+1)\Gamma_p\Gamma_\gamma/\Gamma$ (eV)
835	0.31 ± 0.09
942	1.4 ± 0.4
959	0.23 ± 0.07
978	1.1 ± 0.3
983	1.3 ± 0.4
2187	11 ± 3

[a]) Ref. [7]).

10 W.u. were rejected [12-14]). It often occurs that the M2 estimate is above and the E2 estimate below 10 W.u., in which case one may reject the possibility of parity change for the transition in question.

There are three more sources of information which help to restrict the number of possible J^π values of bound states.

First, one may consider other resonances [10]) (with known J_r or J_r^π) at which no measurements were performed in the present work, but which excite the level in question with a transition which, for the J^π value assumed, would have an unacceptably large quadrupole (or even octupole) strength.

In an analogous way, the known bound-state lifetimes [ref. [10]) and present work] lead to J^π restrictions. Because one would not like to exclude the *a priori* possibility that bound states have considerable collective character, the "acceptability limit" for E2 transitions de-exciting bound states was increased from 10 W.u. to 20 W.u.

Finally, one has to take into account the angular distributions of secondary γ-rays measured in the present work. They were analysed in the same way as explained above for the primary radiation. The theoretical expressions [15]) for a_2 and a_4 are functions of the mixing ratios x and y of the primary and secondary transitions, respectively, of which the former is known from the analysis for the primary radiation. Large y-values and the known bound-state lifetimes may again lead to unacceptably strong quadrupole admixtures.

4. Results

4.1. YIELD MEASUREMENTS

The resonance strengths in the E_p = 0.4-C.8 and 1.0-2.0 MeV regions are accurately known from previous work [7]). Those in the region E_p = 0.8-1.0 MeV were measured in the present investigation. In addition, the strength of the E_p = 2187 keV resonance was remeasured, because it is important in connection with recent calculations of γ-ray transition probabilities by Maripuu [22]). The yield measurements were carried out with a 10 cm × 10 cm NaI(Tl) crystal at an angle of 55° with respect to the proton beam. For more details on the technique of such measurements, see ref. [17]). The strengths were obtained by comparison of the yields with that of the E_p = 620 keV resonance of which the strength is accurately known [16]). The results are presented in table 1. The strength 11±3 eV of the E_p = 2187 keV resonance is in agreement with the values given in refs. [7,8]), e.g. 9.7±1.5 and 8.5±4 eV, respectively.

4.2. LIFETIMES OF BOUND STATES

The lifetime of the 5.67 MeV level and upper limits for the lifetime of the 5.53 and 5.56 MeV levels were obtained from γ-ray Doppler shift measurements at $\theta = 0°$ and $\theta = 140°$. The mean lifetimes were computed from the attenuated Doppler shift F as a fraction of the shift for an infinitely short-lived state. Curves showing F as a function of the mean lifetime τ_m and details of the experimental arrangement and the method of analysis can be found in ref. [10]). The results of the present measurements are given in table 2.

TABLE 2
Lifetime measurements of ^{31}P states

E_x (MeV)	E_p (keV)	Decay to (E_x in MeV)	F (%)	τ_m (fs)
5.53	1830	2.23	97 ± 14	<37
5.56	1667	0	104 ± 9	<25
5.67	1667	1.27	77 ± 9	45 ± 20

TABLE 3
Angular distribution coefficients a_2 and a_4 of γ-rays in the ^{30}Si(p, γ)^{31}P reaction

E_p [a] (keV)	J_r^π [b]	Transition (E_x in MeV)	a_2 [c]	a_4 [c]
1830	$\frac{3}{2}^+$	9.06 → 4.63	-0.06 ± 0.02	$+0.05 \pm 0.03$
		9.06 → 5.53	-0.27 ± 0.15	-0.04 ± 0.16
		4.63 → 2.23	$+0.45 \pm 0.10$	-0.05 ± 0.12
		4.63 → 3.29	$+0.19 \pm 0.07$	$+0.04 \pm 0.08$
1667	$\frac{5}{2}$	8.90 → 5.67	$+0.40 \pm 0.10$	$+0.09 \pm 0.09$
		8.90 → 5.56	-0.43 ± 0.14	$+0.05 \pm 0.15$
		5.67 → 1.27	-0.33 ± 0.09	$+0.12 \pm 0.10$
1595	$\frac{7}{2}$	8.83 → 6.40	$+0.38 \pm 0.09$	-0.03 ± 0.09
		8.83 → 6.93	$+0.03 \pm 0.12$	$+0.03 \pm 0.13$
		6.40 → 4.43	$+0.23 \pm 0.11$	$+0.03 \pm 0.11$
		6.93 → 2.23	-0.25 ± 0.18	$+0.05 \pm 0.19$
1490	$\frac{3}{2}^+$	8.83 → 5.02	-0.46 ± 0.05	
		5.02 → 1.27	$+0.02 \pm 0.13$	
		5.02 → 0	-0.13 ± 0.09	
1301	$\frac{3}{2}^-$	8.55 → 5.01	$+0.48 \pm 0.10$	
		5.01 → 0	-0.03 ± 0.14	
978	$\frac{5}{2}^-$	8.23 → 4.43	-0.29 ± 0.02	0.00 ± 0.02
		8.23 → 5.67	$+0.37 \pm 0.08$	$+0.10 \pm 0.08$
		4.43 → 2.23	-0.25 ± 0.05	$+0.04 \pm 0.06$
		4.43 → 3.29	-0.23 ± 0.03	$+0.03 \pm 0.03$
		5.67 → 1.27	-0.24 ± 0.06	-0.07 ± 0.06
959	$\frac{7}{2}$	8.22 → 3.29	-0.29 ± 0.03	$+0.03 \pm 0.03$
		8.22 → 6.40	$+0.48 \pm 0.23$	$+0.11 \pm 0.23$
		3.29 → 1.27	$+0.33 \pm 0.05$	$+0.08 \pm 0.05$
		3.29 → 2.23	$+0.27 \pm 0.11$	-0.02 ± 0.10
		6.40 → 4.43	$+0.51 \pm 0.13$	$+0.14 \pm 0.12$

[a]) Ref. [7]).
[b]) Ref. [7]) except for the J^π values of the 959 and 978 keV resonances which follow from the present work.
[c]) After correction for eccentricity and absorption but without solid angle attenuation correction.

4.3. ANGULAR DISTRIBUTION MEASUREMENTS

The angular distribution measurements are summarized in table 3, which gives the a_2 and a_4 coefficients of the Legendre series expansion. A short discussion of the conclusions drawn from the data is given below. The numerical data necessary for this discussion are given in fig. 2.

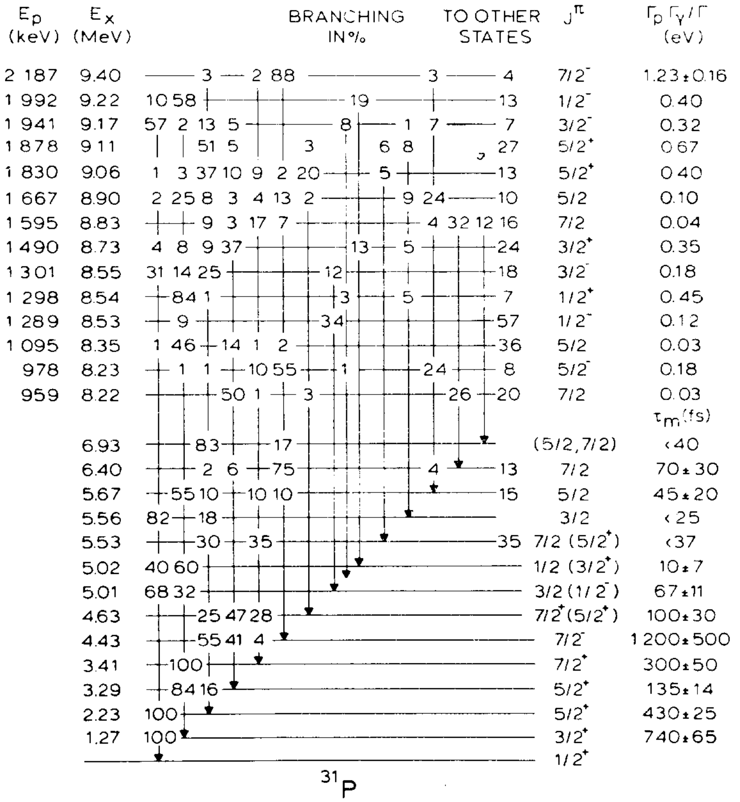

Fig. 2. Partial level scheme of ^{31}P from refs. [7,10]) and present work. Only those levels are indicated which are relevant to the discussion in this paper.

4.3.1. *The* 4.63 MeV *level.* This state is excited only at $J_r = \frac{5}{2}$ or $\frac{7}{2}$ resonances, and it de-excites to $J^\pi = \frac{5}{2}^+$ and $\frac{7}{2}^+$ levels.

The (almost isotropic) angular distribution of the primary at the $E_p = 1830$ keV, $J_r^\pi = \frac{5}{2}^+$, resonance excludes $J = \frac{1}{2}$ and $\frac{9}{2}$. The mixing ratios $x = -0.17 \pm 0.01$ and $+0.41 \pm 0.02$ for $J = \frac{3}{2}$ and $\frac{5}{2}$, respectively, are large enough to exclude odd parity for these spin possibilities. For $J = \frac{7}{2}$, the primary is almost unmixed, $x = +0.06 \pm 0.02$. The mean lifetime $\tau_m = 100 \pm 30$ fs is short such that for $J^\pi = \frac{3}{2}^+$, the E2 decay to the $J^\pi = \frac{7}{2}^+$ 3.41 MeV level would become unacceptably fast. For $J = \frac{7}{2}$, the secondary transitions to the $J^\pi = \frac{5}{2}^+$ 2.23 and 3.29 MeV levels are both strongly mixed with $y = -0.53 \pm 0.10$ and -0.30 ± 0.05, respectively, which, for odd parity, both would imply too large M2 admixtures. One thus concludes that $J^\pi(4.63) = \frac{7}{2}^+$, $(\frac{5}{2}^+)$. The preference for the unbracketed J^π value is based on the fact that it corresponds to a practically unmixed primary, whereas the large mixing ratio for $J^\pi = \frac{5}{2}^+$ level entails a strong (1.8 ± 0.5 W.u.) E2 admixture.

4.3.2. *The* 5.01-5.02 MeV *doublet.* It was shown in ref. [10]) that, although the components have identical excitation energies within the experimental error, $E_x = 5014.9 \pm 1.0$ and 5015.2 ± 0.8 keV, they have very different branching ratios $\gamma_0/\gamma_1 = 2.1 \pm 0.3$ and 0.67 ± 0.08 and mean lifetimes $\tau_m = 67 \pm 11$ and 10 ± 7 fs, respectively.

The 5.01 MeV component is strongly excited at the $E_p = 1289$ keV (34 %) and 1301 keV (12 %) resonances. The primary at the former $J_r^\pi = \frac{1}{2}^-$ resonance is strong enough to exclude $J(5.01) = \frac{5}{2}$. The angular distribution of the primary measured at the latter, $J_r^\pi = \frac{3}{2}^-$, resonance leads for $J(5.01) = \frac{1}{2}$ to $x = -0.60 \pm 0.09$. The measured lifetime then would entail $|M^2(\mathrm{M2})| = 15$ W.u. for $J^\pi(5.01) = \frac{1}{2}^+$.

Therefore $J^\pi(5.01) = \frac{3}{2}, (\frac{1}{2}^-)$.

The 5.02 MeV component is strongly excited at the $E_p = 1490$ keV (13 %) and 1992 keV (19 %) resonances with $J_r^\pi = \frac{3}{2}^+$ and $\frac{1}{2}^-$, respectively. The strength of the latter transition rejects $J(5.02) = \frac{5}{2}$. The same conclusion can be drawn from the 5.02 → 0 MeV angular distribution measured at the former resonance. The primary at this resonance is strongly mixed, $x = +0.79 \pm 0.12$, for $J(5.02) = \frac{3}{2}$, which, together with the known resonance strength, excludes $J^\pi(5.02) = \frac{3}{2}^-$.

Therefore, $J^\pi(5.02) = \frac{1}{2}, (\frac{3}{2}^+)$.

The entirely different angular distributions of the primaries with $a_2 = +0.48 \pm 0.10$ and -0.46 ± 0.05, respectively, measured at the $E_p = 1301$ and 1490 keV resonances (both with $J_r = \frac{3}{2}$) provide another proof, in addition to the difference in branchings and lifetimes, of the doublet character of the "5.0 MeV state".

4.3.3. *The* 5.53 MeV *level.* The reasoning for this level is almost completely analogous to that for the 4.63 MeV level. It is excited at $J_r^\pi = \frac{5}{2}$ resonances, and it de-excites to $J^\pi = \frac{5}{2}^+$ and $\frac{7}{2}^+$ states. The 5.53 MeV level is 6 % excited at the $E_p = 1878$ keV $\frac{5}{2}^+$ resonance, which excludes $J(5.53) = \frac{1}{2}$ and $\frac{9}{2}$. The angular distribution of the primary transition at the $E_p = 1830$ keV, $J_r^\pi = \frac{5}{2}^+$ resonance eliminates $J^\pi(5.53) = \frac{5}{2}^-$. The lifetime upper limit $\tau_m < 37$ fs eliminates $J = \frac{3}{2}$. The mixing of the primary is small for $J = \frac{7}{2}$ and large ($x = +0.52 \pm 0.12$) for $J^\pi = \frac{5}{2}^+$.

Therefore, $J^\pi = \frac{7}{2}, (\frac{5}{2}^+)$.

4.3.4. *The* 5.56 MeV *level.* The level is excited at $J_r = \frac{1}{2}, \frac{3}{2}$ and $\frac{5}{2}$ resonances and de-excites to $J^\pi = \frac{1}{2}^+$ and $\frac{5}{2}^+$ levels.

The angular distribution of the primary at the $E_p = 1667$ keV, $J_r = \frac{5}{2}$ resonance eliminates $J = \frac{1}{2}$ and $\frac{9}{2}$. The lifetime upper limit $\tau_m < 25$ fs leads to a fast ground-state transition, which is incompatible with $J = \frac{7}{2}$ or $J^\pi = \frac{5}{2}^-$. Finally, one can reject $J^\pi = \frac{5}{2}^+$ because the 5 % primary at the $E_p = 1298$ keV, $J_r^\pi = \frac{1}{2}^+$ resonance would be too strong (20 W.u.) for an E2 transition.

Therefore, $J(5.56) = \frac{3}{2}$.

4.3.5. *The* 5.67 MeV *level.* The decay of the level to $J^\pi = \frac{3}{2}^+, \frac{5}{2}^+, \frac{7}{2}^+$ and $\frac{7}{2}^-$ states together with the short mean lifetime $\tau_m = 45 \pm 20$ fs very much restricts the J^π possibilities; only $J^\pi = \frac{5}{2}$ and $\frac{7}{2}^+$ remain. The latter possibility is not valid because the level is excited (7 %) at the $E_p = 1941$ keV, $J_r^\pi = \frac{3}{2}^-$ resonance. One is thus left with $J = \frac{5}{2}$, which is also the only spin value for which the angular distribution of the primary measured at the $E_p = 1667$ keV, $J_r = \frac{5}{2}$ resonance leads to vanishing mixing, $x = -0.01 \pm 0.09$.

Therefore, $J(5.67) = \frac{5}{2}$.

4.3.6. *The* 6.40 MeV *level.* The mean lifetime $\tau_m = 70 \pm 30$ fs together with the decay to $\frac{5}{2}^+$ and $\frac{7}{2}^-$ states leads to $J^\pi = \frac{5}{2}, \frac{7}{2}$ or $\frac{9}{2}^+$. The angular distribution of the primary measured at the $E_p = 1595$ keV, $J_r = \frac{7}{2}$ resonance is not very informative, mainly because the resonance parity is unknown. It leads to $x = -0.38 \pm 0.05$, $+0.07 \pm 0.09$ and 0.45 ± 0.10 for $J(6.40) = \frac{5}{2}, \frac{7}{2}$ and $\frac{9}{2}$, respectively. The angular distribution of the secondary to the 4.43 MeV $\frac{7}{2}^-$ level, however, entails $y = +0.37 \pm 0.13$, $+0.16 \pm 0.14$ and -0.33 ± 0.07 for the same 6.40 MeV spins, which eliminates, because of unacceptably large M2 admixtures, the $J^\pi = \frac{5}{2}^+$ and $\frac{9}{2}^+$ possibilities.

Therefore, $J^\pi(6.40) = \frac{7}{2}, (\frac{5}{2}^-)$.

It will be shown below that $J^\pi = \frac{5}{2}^-$ can be rejected with the aid of the data obtained at the $E_p = 959$ keV resonance.

4.3.7. *The* 6.93 MeV *level.* Both the measured angular distribution of the primary measured at the $E_p = 1595$ keV, $J_r = \frac{7}{2}$ resonance and its strength eliminate $J(6.93) = \frac{3}{2}$. The upper limit on the mean lifetime $\tau_m < 40$ fs and the decay to $\frac{5}{2}^+$ and $\frac{7}{2}^-$ states further restrict the possibilities to $J^\pi = \frac{5}{2}, \frac{7}{2}, \frac{9}{2}^+$. The latter J^π value can be rejected with the aid of the angular distribution of the secondary to the 2.23 MeV $\frac{5}{2}^+$ level and also by the occurrence of a 3 % primary at the $E_p = 1095$ keV, $J_r = \frac{5}{2}$ resonance.

Therefore, $J(6.93) = (\frac{5}{2}, \frac{7}{2})$.

4.3.8. *The* $E_p = 959$ keV *resonance* ($E_x = 8.22$ MeV). It is shown in fig. 1 that the angular distribution of the primary to the 3.29 MeV $\frac{5}{2}^+$ level eliminates $J_r = \frac{1}{2}, \frac{5}{2}$ and $\frac{9}{2}$. Next the angular distribution of the r → 6.40 MeV transition was analysed for $J_r = \frac{3}{2}$ and $\frac{7}{2}$ and $J(6.40) = \frac{5}{2}$ and $\frac{7}{2}$. It was found that the combinations $J_r = \frac{3}{2}$, $J(6.40) = \frac{5}{2}$ and $J_r = \frac{7}{2}$, $J(6.40) = \frac{5}{2}$, both lead to large mixing ratios, $x = 0.81 \pm 0.28$ and -0.49 ± 0.09, respectively, implying unacceptably strong quadrupole admixtures. For $J_r = \frac{3}{2}$, $J(6.40) = \frac{7}{2}$, the transition in question would have pure quadrupole character which is *a fortiori* excluded. For $J_r = J(6.40) = \frac{7}{2}$ the mixing ratios of both the r → 3.29 MeV (see fig. 1) and the r → 6.40 MeV transition are vanishingly small.

Therefore, $J_r = \frac{7}{2}$, $J(6.40) = \frac{7}{2}$.

4.3.9. *The* 978 keV *resonance* ($E_x = 8.23$ MeV). The angular distributions of the primaries to the 4.43 MeV, $J^\pi = \frac{7}{2}^-$ and 5.67 MeV, $J = \frac{5}{2}$ levels eliminate all assignments but $J_r = \frac{5}{2}$. For the former primary, one finds $x = -0.12 \pm 0.01$, which is large enough to exclude even parity for the resonance. The latter primary is practically unmixed.

Therefore, $J_r^\pi = \frac{5}{2}^-$.

4.4. MIXING RATIOS

The mixing ratios following from the present work are summarized in table 4. Most of the values are seen to be quite small. The two possibilities for the mixing ratio of the 5.67 → 1.27 MeV transition determined at the E_p = 1667 keV resonance are in good agreement with the values determined at the E_p = 978 keV resonance. There is a difference between the mixing ratio of the 6.40 → 4.43 MeV transition obtained at the E_p = 1595 keV resonance and the value obtained at the E_p = 959 keV resonance, but the difference remains almost within the combined experimental error.

TABLE 4

Quadrupole/dipole amplitude mixing ratios of transitions between ^{31}P levels as determined in the present work

E_p (keV)	Transition (E_x in MeV)	J_i^π	J_f^π	Mixing ratio
1667	8.90 → 5.67	$\frac{5}{2}$	$\frac{5}{2}$	−0.01 ± 0.09
	8.90 → 5.56	$\frac{5}{2}$	$\frac{3}{2}$	+0.03 ± 0.06
	5.67 → 1.27	$\frac{5}{2}$	$\frac{3}{2}^+$	+0.03 ± 0.08 or
				+3.3 ± 1.3
1595	8.83 → 6.40	$\frac{7}{2}$	$\frac{7}{2}$	+0.07 ± 0.09
	6.40 → 4.43	$\frac{7}{2}$	$\frac{7}{2}^-$	+0.15 ± 0.14
1301	8.55 → 5.01	$\frac{3}{2}^-$	$\frac{3}{2}$	−0.09 ± 0.08
	5.01 → 0	$\frac{3}{2}$	$\frac{1}{2}^+$	−0.17 ± 0.46
978	8.23 → 4.43	$\frac{5}{2}^-$	$\frac{7}{2}^-$	−0.12 ± 0.01
	8.23 → 5.67	$\frac{5}{2}^-$	$\frac{5}{2}$	+0.01 ± 0.08
	4.43 → 2.23	$\frac{7}{2}^-$	$\frac{5}{2}^+$	−0.03 ± 0.02
	4.43 → 3.29	$\frac{7}{2}^-$	$\frac{5}{2}^+$	−0.04 ± 0.03
	5.67 → 1.27	$\frac{5}{2}$	$\frac{3}{2}^+$	+0.04 ± 0.04 or
				+3.2 ± 0.5
959	8.22 → 3.29	$\frac{7}{2}$	$\frac{5}{2}^+$	−0.03 ± 0.01
	8.22 → 6.40	$\frac{7}{2}$	$\frac{7}{2}$	−0.11 ± 0.28
	6.40 → 4.43	$\frac{7}{2}$	$\frac{7}{2}^-$	−0.34 ± 0.32
	3.29 → 1.27	$\frac{5}{2}^+$	$\frac{3}{2}^+$	−0.42 ± 0.04
	3.29 → 2.23	$\frac{5}{2}^+$	$\frac{5}{2}^+$	+0.12 ± 0.10

5. Discussion

There is no other information with which the present J^π value for the 4.63 MeV level can be compared. It was stated already in ref. [10]) that the data of ref. [3]) actually refer to the 4.59 MeV and not to the 4.63 MeV level.

One of the components of the 5.01-5.02 MeV doublet is excited in both the ^{30}Si(d, n)^{31}P and ^{30}Si(^{3}He, d)^{31}P reactions with a strong $l_p = 1$ transition [18,19]). The excitation energies from the two reactions are given as 5010 ± 10 and 5030 ± 15 keV, respectively, and the J-dependence of the (d, n) angular distribution led to a $J^\pi = \frac{3}{2}^-$

assignment. The large spectroscopic factor observed in the (^{3}He, d) work points to rather pure $2p_{\frac{3}{2}}$ single-particle character. From the J^π limitation obtained in the present work, it is clear that this state can only be identified with the 5.01 MeV component of the doublet.

The angular distribution of the r → 5.02 MeV together with the 5.02 → 1.27 MeV transition was also measured at the E_p = 1490 keV resonance (as in the present work) by Harris and Seagondollar [1]). The transitions are too close in energy to be resolved by their NaI detector. If the correct branching ratio (γ_0/γ_1 = 0.67 instead of 2.3) is used in the analysis of their result, it is found to be in good agreement with the present measurement. Neither of the two measurements leads to a determination of the parity of the 5.02 MeV level contrary to what is stated in ref. [1]).

One of the few mixing ratios of table 4, which is definitely non-zero, is that for the

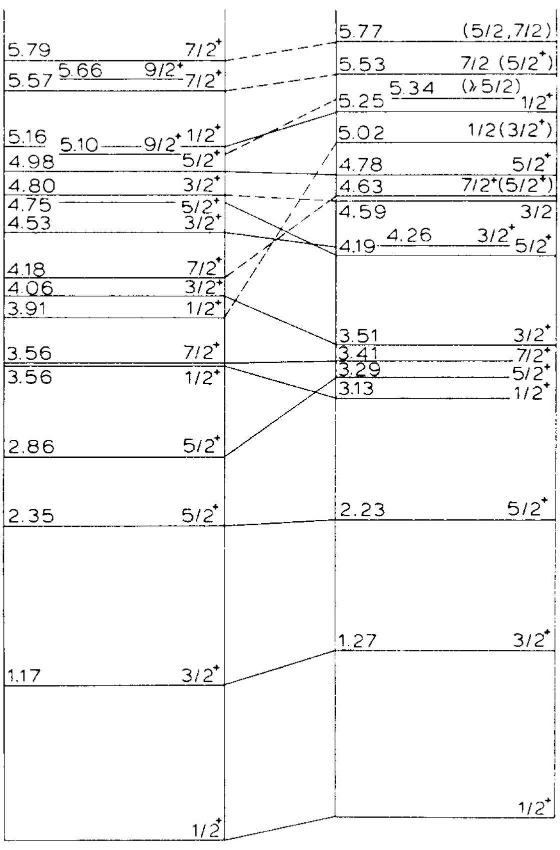

Fig. 3. Comparison of theoretical and experimental excitation energies of even-parity states in ^{31}P. In the theoretical level scheme [24]) up to four states (below E_x = 5.8 MeV) are given for each spin value. In the experimental level scheme, all states below 5.8 MeV are given which have or might have even parity.

3.29 → 1.27 MeV transition, $x = -0.42 \pm 0.04$. It is in good agreement with the values given in refs. [3,6]), $x = -0.44 \pm 0.02$ and -0.37 ± 0.02, respectively. The small value, $x = +0.12 \pm 0.10$ found for the 3.29 → 2.23 MeV transition is in agreement with that in ref. [6]), $x = -0.05 \pm 0.06$ but in disagreement with the value in ref. [3]), $x = -0.41 \pm 0.06$. It was already pointed out in ref. [10]) that the latter value would have led to a very large E2 strength of 17 W.u.

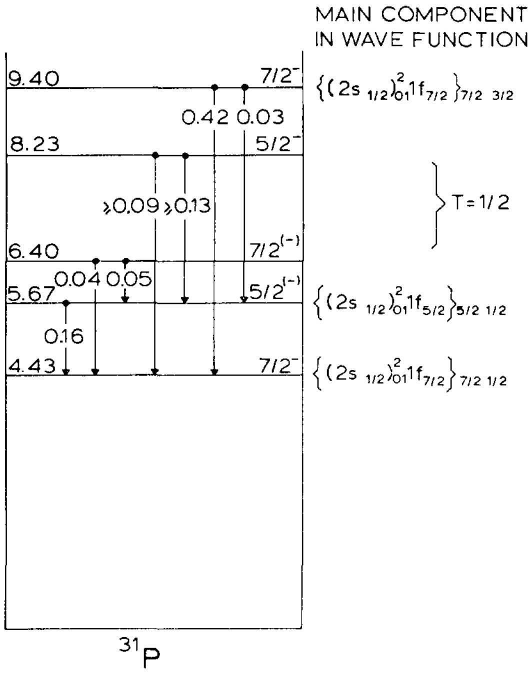

Fig. 4. States in ^{31}P with $J^{\pi} = \frac{5}{2}^-$ and $\frac{7}{2}^-$. The strengths of M1 transitions between these states are given in Weisskopf units. The two indices in the main wave-function components indicate J and T.

Theoretically, by far the most successful treatment of the ^{31}P level scheme is the recent shell-model calculation by Wildenthal *et al.* [24]), which considers particles in the $2s_{\frac{1}{2}}$ and $1d_{\frac{3}{2}}$ shells and up to two holes in the $1d_{\frac{5}{2}}$ shell. The interaction is assumed to be of the modified surface delta type. The number of many-particle states for given A, J and T is typically between 100 and 300. The calculation fitting the excitation energies of 53 even-parity states in the $A = 30$-33 region with only seven parameters yields an average absolute deviation of 270 keV. The result for ^{31}P is given in fig. 3. Of the 18 calculated states below $E_x = 5.8$ MeV, 17 are seen to have a corresponding experimental state. If all theoretical states are increased in energy by 170 keV (which is equal to the deviation in the binding energy), the remaining average absolute deviation is only 220 keV. The largest deviation occurs for the third $\frac{1}{2}^+$ state for which the calculation yields $E_x = 3.91$ MeV, whereas the lowest possible experimental candidate above 3.13 MeV is the 5.02 MeV level.

The wave functions of ref. [24]) are also used at present to compute M1 and E2 transition probabilities. The initial results are very promising [25]).

Let us next consider the ^{31}P states with more or less pronounced f-wave character (see fig. 4). In the following, only those states shall be taken into account in which a $1f_{\frac{7}{2}}$ or $1f_{\frac{5}{2}}$ particle is coupled to a $(2s_{\frac{1}{2}})^2_{J_1, T_1}$ core with $J_1, T_1 = 0, 1$ or $1, 0$. In this group, there are four $J^\pi = \frac{7}{2}^-$ and four $J^\pi = \frac{5}{2}^-$ states. One of each subgroup has $T = \frac{3}{2}$, the analogue states (of which the $\frac{7}{2}^-$ analogue is known to occur at $E_x = 9.40$ MeV), the other six have $T = \frac{1}{2}$. The states with the same J and T are expected to be mixed, of course. The three $s^2f_{\frac{7}{2}}$ states coupled to $\frac{7}{2}^-$ have recently been discussed by Maripuu [22]). The 4.43 MeV $\frac{7}{2}^-$ level is known to have outspoken $(s^2_{01}f_{\frac{7}{2}})_{\frac{7}{2}\frac{1}{2}}$ character because it is strongly excited in the ^{30}Si(^{3}He, d) reaction [19,26]).

The 5.67 MeV $J = \frac{5}{2}$ level is equally strongly excited in the same reaction [26]). In both inelastic electron scattering [20]) (at $E_e = 130$ and 180 MeV) and inelastic proton scattering[21]) (at $E_p = 155$ MeV), E3 excitation has been observed to a state of which the excitation energy is given as 5.67 ± 0.07 and 5.6 ± 0.1 MeV, respectively. In addition, the 5.67 MeV level is connected with strong dipole transitions to the f-states at 4.43, 8.23 and 9.40 MeV. These arguments make it very probable that one can assign odd parity to the 5.67 MeV level, and that this state has predominantly $(s^2_{01}f_{\frac{5}{2}})_{\frac{5}{2}\frac{1}{2}}$ character.

It is also tempting to assume odd parity for the 6.40 MeV $J = \frac{7}{2}$ level, mainly because it strongly decays to the 4.43 and 5.67 MeV levels. Finally, also the 8.23 MeV $J^\pi = \frac{5}{2}^-$ state could be included in the present set of s^2f states.

Also shown in fig. 4 are the strengths of M1 transitions proceeding between the f-states discussed above. They range from 0.03 to 0.42 W.u. with an average of 0.13 W.u., which agrees with the average [14]) for all known M1 transitions in the s-d shell, which is about 0.1 W.u. This contrasts sharply with the strength of the 16 E1 transitions de-exciting the states of fig. 4 to lower-lying even-parity states. From the data in ref. [10]) and the present work, one finds that their strengths range from 8×10^{-6} to 2.4×10^{-4} W.u. with an average of 1.0×10^{-4} W.u., which is 20 times smaller than the s-d shell average [14]) of 2×10^{-3} W.u. Taking into account the fact that, for the same E_γ, the M1 Weisskopf estimate is 3 % of that for E1, one obtains the curious result that in ^{31}P, again for the same E_γ, the average Γ_γ for M1 is 40 times that for E1. One thus obtains a system of f-states, which is interconnected by strong transitions and very weakly connected to the system of even-parity states.

It would seem as if the above argumentation is weakened because, mainly for the 6.40 MeV level, the strong dipole transitions connecting it to f-states previously were used to assign odd parity to this level. These two transition strengths are below the ^{31}P M1 average, however, such that exclusion of the 6.40 MeV level strengthens rather than weakens the argument for a large M1/E1 strength ratio.

Finally, a remark should be made about the separation of single-particle states in ^{31}P. In the following it will be assumed that the main components of the $1f_{\frac{7}{2}}$, $2p_{\frac{3}{2}}$ and $1f_{\frac{5}{2}}$ strengths are to be found at 4.43, 5.01 and 5.67 MeV, respectively. No $\frac{1}{2}^-$ state has as yet been located, but both the 6.50 and 6.61 MeV levels have relatively strong p-wave character [19]) [see also ref. [26])], such that at least one of these might well have $2p_{\frac{1}{2}}$ character. The $2p_{\frac{3}{2}}$, $1f_{\frac{5}{2}}$ and $2p_{\frac{1}{2}}$ levels are then situated 0.6, 1.2 and 2.1 MeV, respectively, above the $1f_{\frac{7}{2}}$ level. In ^{41}Ca, the separations for these same levels [27]) again compared to the $1f_{\frac{7}{2}}$ level, are 2.1, 5.5 and 4.1 MeV, respectively, such that the four fp states in ^{31}P are compressed into a 0.38 times smaller region. In addition, the order of the $2p_{\frac{1}{2}}$ and $1f_{\frac{5}{2}}$ states has been inverted. The compression effect can be understood qualitatively, if the Tabakin interaction is used for the calculation of the necessary two-particle energies [25]). For example, the splitting between the two f-states diminishes from ^{41}Ca to ^{31}P because the interaction between $d_{\frac{3}{2}}$ and $f_{\frac{7}{2}}$ particles is larger than between $d_{\frac{3}{2}}$ and $f_{\frac{5}{2}}$.

As a conclusion, one might say that relatively simple Ge(Li) angular distribution measurements can provide a large amount of new information. In the present case, the interpretation of the data is greatly helped by the existing body of knowledge on J^{π} values, resonance strengths, lifetimes and branchings in ^{31}P. Especially needed at present are more determinations of resonance parities, which, in turn, could lead to the removal of existing ambiguities in the spins and parities of bound states.

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