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Excited states of ^{30}P investigated through the ^{29}Si(^{3}He, d)^{30}P reaction

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Abstract. The Oxford multigap spectrometer has been used in a study of the ^{29}Si(^{3}He, d)^{30}P reaction at an incident ^{3}He energy of 15 MeV. Twenty-eight states in ^{30}P have been identified up to an excitation energy of about 6 MeV. Parity assignments have been made from a DWBA analysis of the angular distributions, spin restrictions have been placed on some levels while the 3·731 MeV level has been assigned $J^\pi = 1^+$. Spectroscopic factors have been obtained and compared with theoretical values. The results are discussed with respect to model calculations.

1. Introduction

The level scheme of ^{30}P has been examined extensively through various γ ray decay studies as well as a ^{32}S(d, α)^{30}P reaction study.

Levels up to 4·92 MeV excitation in ^{30}P were examined by Harris and Hyder (1967) and Harris *et al* (1969) through ^{29}Si(p, γ)^{30}P resonance reactions using techniques of angular correlations, lifetime and polarization measurements. Also Vermette *et al* (1968) studied states in ^{30}P up to 4·92 MeV excitation using the ^{28}Si(^{3}He, pγ)^{30}P reaction. Using the ^{32}S(d, α)^{30}P reaction Endt and Paris (1958) observed 30 levels in ^{30}P below 5·8 MeV excitation.

Of the 34 levels now known below 5·8 MeV in ^{30}P only 17 spin and parity assignments have been made together with 4 other restrictions according to the recent tabulation by Endt and van der Leun (1973).

The experiment is described in § 2 and a brief discussion of the DWBA analysis is given in § 3. The experimental angular distributions allow us to determine the proton l_p transfer and parities of all but two of the states observed. Spin restrictions have been placed on several levels and the results have been compared with existing information on this nucleus.

2. Experimental procedure

A 15 MeV ^{3}He^{++} beam from the Oxford Nuclear Physics Laboratory Van de Graaff generator was used to bombard an enriched ^{29}Si (95 % ^{29}Si, 4·7 % ^{28}Si and 0·3 % ^{30}Si) self-supporting target of thickness 66 ± 5 μg cm^{-2}. The reaction particles were detected

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in a multigap spectrometer at 15 angles from 3·75° to 56·25° in 3·75° intervals. Thin polythene foils were laid over the Ilford L4 emulsion plates to stop reaction-produced α particles. Proton–deuteron discrimination was achieved on the basis of kinematics and track identification.

The individual gaps in the Oxford multigap spectrometer are separated by 7·5° intervals but the spectrometer may be rotated through 3·75° so that angular distributions can be obtained from data collected at 3·75° intervals. This procedure was carried out in the present experiment and necessitated two separate exposures of the photographic plates. An integrated beam charge of 500 μC was collected at each spectrometer setting, thus no normalization was required between the two exposures.

Figure 1 shows a spectrum for one of the gaps obtained at a laboratory angle of 15°. The corresponding energy resolution is 22 to 25 keV FWHM. No attempt was made to measure the excitation energies of ^{30}P accurately but level identification was made by an approximate calibration of the spectrometer and the level energies quoted in § 4 of the text were obtained from the compilation of Endt and van der Leun (1973).

Absolute cross sections were obtained from target thickness measurements using weighing techniques together with measurements of the integrated beam charge. The overall accuracy in the absolute cross sections is believed to be ±15%.

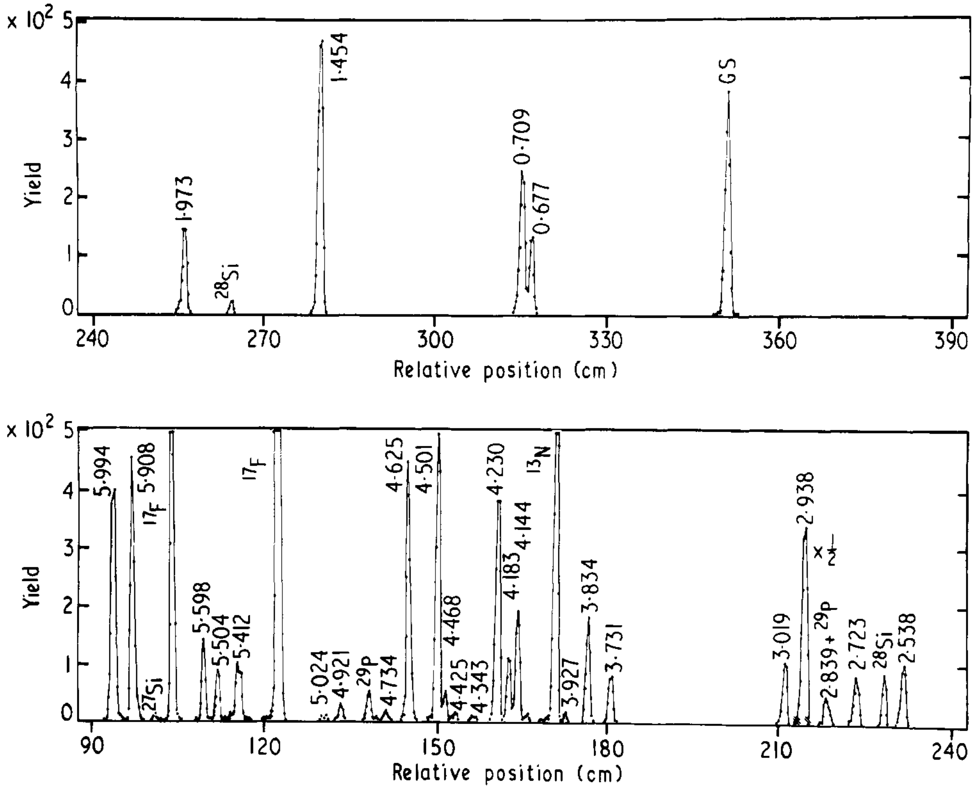

Figure 1. A deuteron spectrum of the $^{29}Si(^{3}He, d)^{30}P$ reaction measured at θ (lab) = 15° in the Oxford multigap spectrograph. The numbers above each peak label the corresponding ^{30}P excitation energy (MeV) taken from Endt and van der Leun (1973). Peaks due to contaminants are identified by their reaction kinematics and are labelled with the name of the residual nucleus formed in the reaction. The yield is the number of tracks counted in a $\frac{1}{4}$ mm scan.

3. DWBA analysis

The procedure used for extracting spectroscopic information from the experimental data consists of comparing the shapes of the experimental angular distributions with those calculated by a DWBA computer code (Hutton J L and Jones G D 1966, unpublished) assuming the transferred proton is captured into single particle states. When a satisfactory fit is obtained the orbital angular momentum transfer l_p is deduced and the parity of the corresponding ^{30}P state is known.

The experimental absolute cross sections are related to the theoretical angular distributions through the spectroscopic factor $S_{l,j}$ in the following way:

$$\frac{d\sigma}{d\Omega}(\theta) = N[(2J_f+1)/(2J_i+1)]C^2\sum_{l,j} S_{l,j}\sigma_{l,j}(\theta)$$

where J_i and J_f are the spins of the initial and final states in the target and residual nucleus respectively, l the orbital angular momentum transfer, j the total angular momentum transfer of the captured proton, $S_{l,j}$ the spectroscopic factor for a single particle transfer (l, j) to the state formed, $\sigma_{l,j}(\theta)$ the cross section obtained from a DWBA calculation for a single particle l, j transfer and N a normalization factor which Bassel (1966) has determined as 4·42 for the (^{3}He, d) reaction. The isopin Clebsch–Gordan coefficient C is defined in French and MacFarlane (1961) and has the value $\sqrt{\frac{1}{2}}$ for both final state isopin values of $T = 0$ and $T = 1$ observed in the present work.

A stripping reaction from an odd-mass target to an even-mass residual nucleus is more complex to analyse than stripping from an even-mass target to an odd-mass residual nucleus because of the possibility of more than one (l, j) satisfying the angular momentum coupling conditions. This can give rise to the incoherent summation of different (l, j) components in the observed angular distributions. In the cases of angular distributions where it is apparent that different (l, j) values have contributed to form the final differential cross sections an attempt has been made to extract the component due to each (l, j) in order to extract meaningful spectroscopic factors.

The values of the parameters used in the optical model potentials to calculate the ^{3}He and deuteron distorted wavefunctions are listed in table 1. These parameter sets represent optimum fits to 15 MeV ^{3}He elastic scattering on ^{30}Si obtained by Morrison (1970) and to 11·8 MeV deuteron elastic scattering on ^{27}Al obtained by Jones *et al* (1968). The optical model potentials were parametrized in the following way:

$$V(r) = -U(1+e^x)^{-1} - i\left(W - 4W_D\frac{d}{dx'}\right)(1+e^{x'})^{-1} + V_c(r)$$

where $x = (r - r_u A^{1/3})/a_u$, $x' = (r - r_w A^{1/3})/a_w$ and $V_c(r)$ is the Coulomb potential for a uniformly charged sphere of radius $1{\cdot}3A^{1/3}$ fm.

Table 1. Optical model parameters

	U (MeV)	r_u (fm)	a_u (fm)	W (MeV)	W_D (MeV)	r_w (fm)	a_w (fm)
^{3}He	173·0	1·07	0·795	18·6	0	1·657	0·762
d	91·08	1·20	0·78	0	27·4	1·51	0·48
For captured proton r_p = 1·33 fm, a_p = 0·5 fm							

The transferred proton bound state wavefunctions were generated by a Saxon–Woods potential well of radius parameter 1·33 fm and diffuseness 0·5 fm, a Coulomb potential and a spin–orbit strength of 25 times the Thomas term. The depth of the real well was adjusted to give the correct binding energy for the bound levels; for the highest few unbound levels the binding energy used in the DWBA calculations was not the correct value but was allowed to keep the final proton in ^{30}P just bound to allow the captured particle wavefunction to converge.

4. Results

Each deuteron group corresponding to one of the 28 levels observed below 6 MeV excitation in ^{30}P is labelled in figure 1. The reaction products from impurities which have been identified by reaction kinematics are also labelled.

The transferred angular momenta were determined from the angular distributions which are shown in figures 2 and 3. The spectroscopic strengths $(2J_f + 1)S$ are listed for individual levels in table 2 and the summed strengths for the transfer of protons to the same single particle orbits are given in table 3.

Ten low-lying levels seen in this reaction have been discussed in a preliminary report (Greene *et al* 1970) from this laboratory and the remaining levels are discussed below according to l_p transfer.

Other DWBA fits were attempted with l_p values or combinations of l_p values different from the ones discussed in the text however as these fits were in all cases unsatisfactory they have been omitted from figures 2 and 3.

4.1. Levels excited with $l_p = 0$ transfers

Figure 2 shows the experimental angular distributions for the levels which are wholly or partly excited by $l_p = 0$ transfer.

4.1.1. The 0, 0·677 and 0·709 MeV levels. The experimental angular distributions leading to the ground and 0·677 MeV states are well fitted by pure single particle $l_p = 0$ transfers in accordance with their known respective $J^\pi = 1^+$ and 0^+ assignments (Endt and van der Leun 1973). The distribution leading to the 0·709 MeV level requires an admixture of $l_p = 2$ to obtain a satisfactory theoretical fit which confirms previous $J^\pi = 1^+$ assignments to the level. The spectroscopic factor for the $l_p = 2$ component in the distribution incorrectly reported by Greene *et al* (1970) by a factor of 10 due to a typographical error is now correctly listed in table 2.

4.1.2. The 2·839 MeV level. The level appearing at an excitation energy of 2·839 MeV in ^{30}P in figure 1 is believed to have been misinterpreted by Greene *et al* (1970). The ^{28}Si(^{3}He, d)^{29}P reaction from the ^{28}Si impurity in the target leading to the ground state of ^{29}P lies very close to the energy expected for the 2·839 MeV level in ^{30}P but the data of Ejiri *et al* (1966) for the ^{28}Si(^{3}He, d)^{29}P reaction indicated that the cross section leading to the ground state of ^{29}P would be negligible for the small ^{28}Si target impurity in the present experiment. However, data obtained by Mertens *et al* (1970) from the ^{28}Si(^{3}He, d)^{29}P reaction obtained at bombarding energies closer to the one used in the present experiment show that the cross section leading to the ground state of ^{29}P from the 4·7 % ^{28}Si impurity in our ^{29}Si target is indeed sufficient to account for all the cross

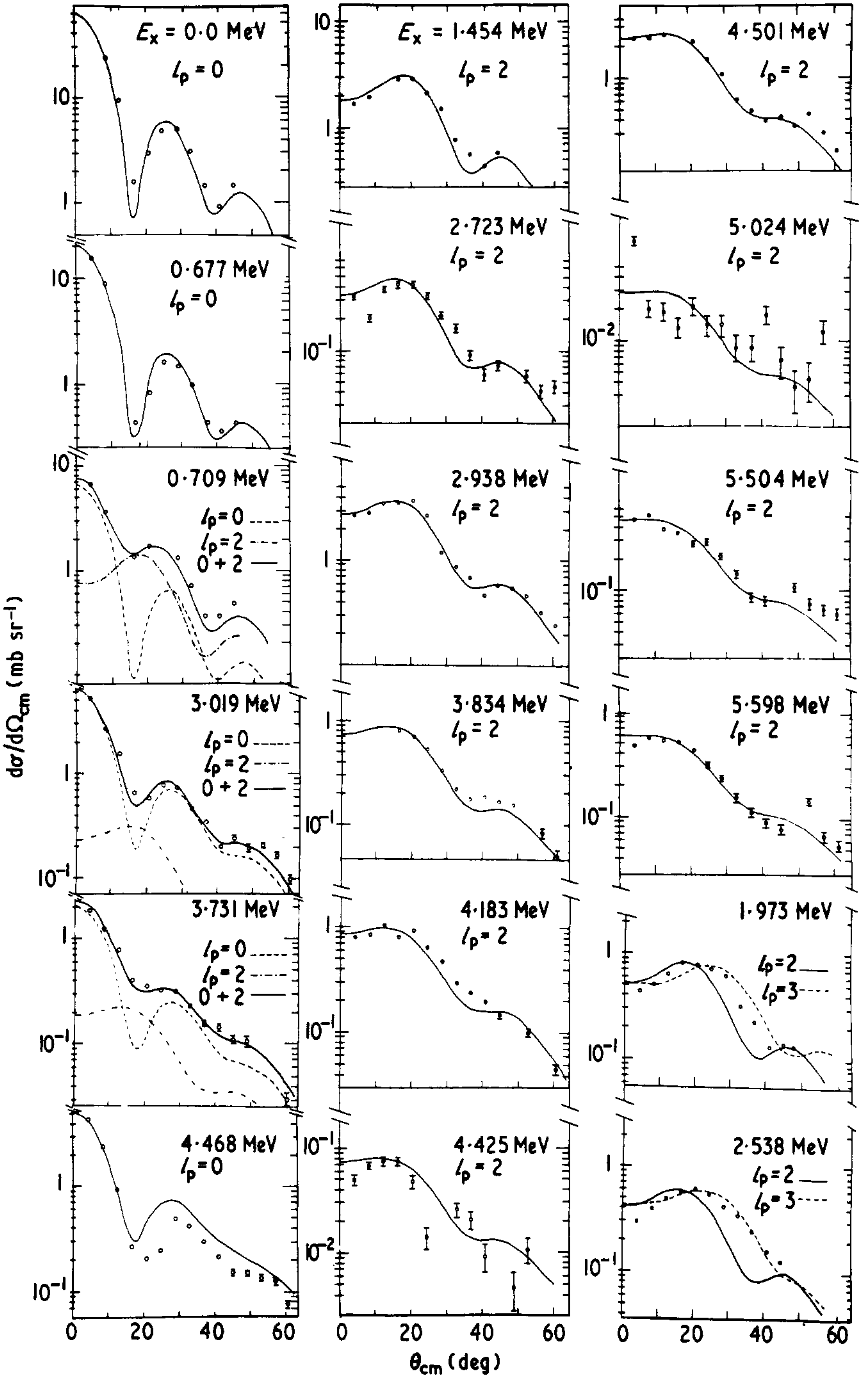

Figure 2. Angular distributions for even-parity levels excited in the ^{29}Si(^{3}He, d)^{30}P reaction, the full curves being DWBA calculations. The experimental data for the levels excited at 0·709, 3·019 and 3·731 MeV were fitted assuming $l_p = 0$ and $l_p = 2$ transfers. Each component and the sum is shown in the fitted angular distributions for these levels. For the levels at 1·973 and 2·538 MeV the non-allowed $l_p = 3$ DWBA calculation gives a good fit to the data. Only statistical errors are included with the experimental points.

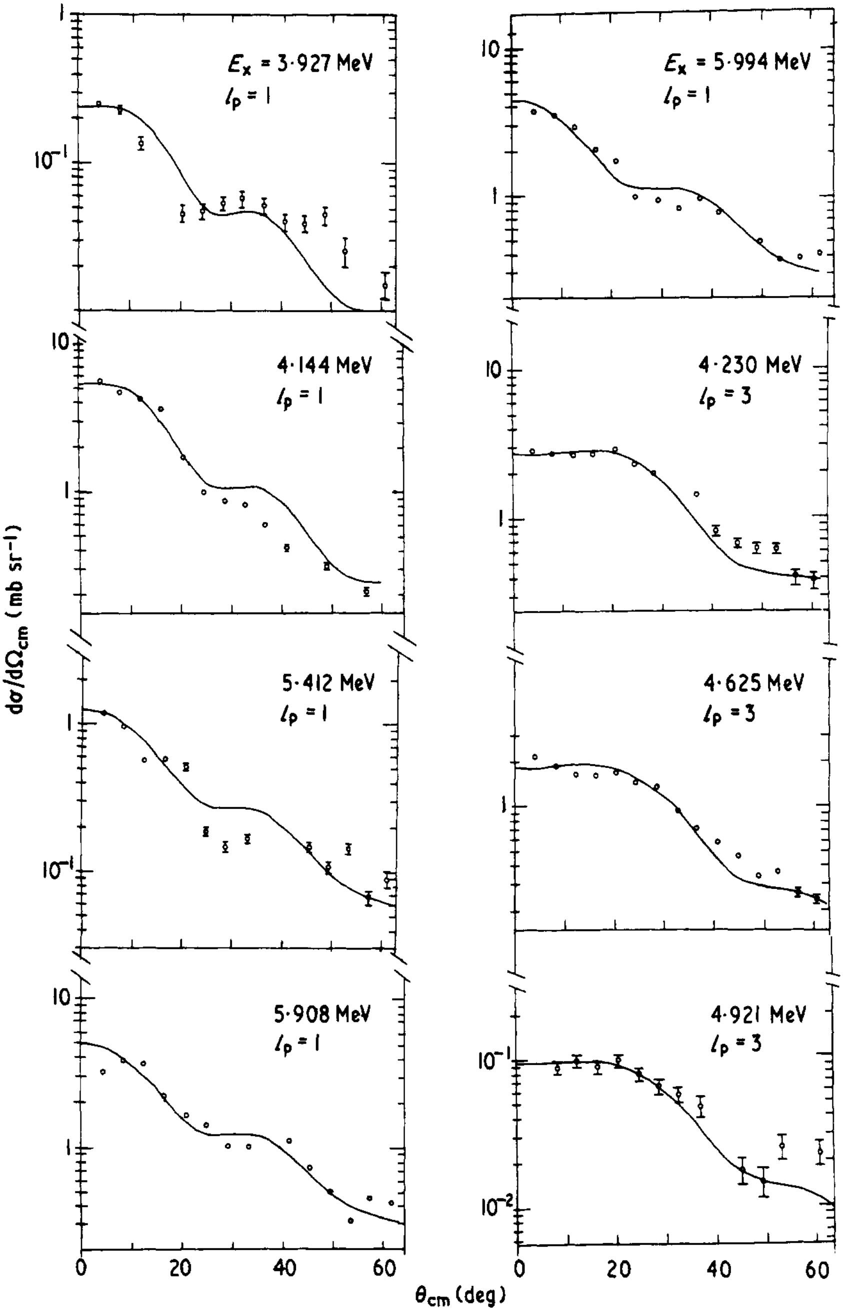

Figure 3. Angular distributions for odd-parity levels excited in the $^{29}Si(^3He, d)^{30}P$ reaction, the full curves being DWBA calculations. The errors on the experimental points are purely statistical.

section observed in the present experiment at the excitation energy corresponding to the 2·839 MeV level in ^{30}P.

Table 2. Experimental and theoretical spectroscopic information for ^{30}P; the isospin of known $T = 1$ levels is indicated

E_x (MeV)	l_p	J^π	$(2J_f+1)S$		
			Experiment	Collective†	Shell model‡
0	0	1^+	2·89	0·53 ($l_p = 0$)	1·39 ($l_p = 0$)
				0·11 ($l_p = 2$)	2·25 ($l_p = 2$)
0·677	0	0^+ ($T = 1$)	1·00	0·53	1·45
0·709	0	1^+	0·37	1·07 ($l_p = 0$)	4·61 ($l_p = 0$)
	2		1·38	0·05 ($l_p = 2$)	0·67 ($l_p = 2$)
1·454	2	2^+	3·25	3·23	5·00
1·973	2	3^+	0·28	0·48	
2·538	2	3^+	0·42	0·36	
2·723	2	2^+	0·40	2·00	
2·839§	if observed				
2·938	2	2^+ ($T = 1$)	3·30	0·47	4·72
3·019	0	1^+	0·46		
	2		0·21		
3·731	0	1^+‖	0·22		
	2		0·09		
3·834	2	$2^+, 1^+$‖	0·55		
3·927	1	1^-‖	0·48		
4·144	1	2^-	1·05		
4·183	2	2^+ ($T = 1$)	0·60		
4·230	(3)¶	4^-	(5·40)¶		
4·343§					
4·425	2	2^+	0·50		
4·468	0	0^+ ($T = 1$)	0·76		0·55
4·501	2	1^+ ($T = 1$)	1·59		3·00
4·625	3	3^-	2·59		
4·734§					
4·921	3	3^-‖	0·14		
5·024§					
5·412	1	$(0–2)^-$‖	1·81		
5·504	2	$(1–3)^+$‖	0·30		
5·598	2	$(1–3)^+$‖	0·42		
5·908	1	$2^-, 1^-$‖	2·00		
5·994	1	1^-‖	1·17		

† Collective model calculation based on the assumption of a proton captured to an oblate ^{29}Si core.

‡ Shell model calculations taken from Glaudemans *et al* (1964) for the analogous ^{29}Si(d, n)^{30}P reaction.

§ The corresponding deuteron group is weak, no fit was attempted.

‖ New spin or parity assignment made with the assistance of data from the present experiment.

¶ Possible excitation of both members of a doublet.

As the angular distribution leading to the ground state of ^{29}P is shown by Mertens *et al* (1970) to be a pure $l_p = 0, j = \frac{1}{2}$ transfer and this is the dominant (but perhaps not the only) l_p transfer observed for the composite 2·839 MeV plus ^{29}P ground state angular distribution (labelled as the 2·839 MeV state by Greene *et al* 1970) it is now not clear to what extent the 2·839 MeV state in ^{30}P was excited in the present work. Further

Table 3. Comparison of summed strengths $\Sigma\,(2J_f+1)S$ with sum rule limits of French and MacFarlane (1961) and the location of the single particle centroids

Proton transferred	Final state isospin T	Summed strength measured	Summed strength sum rule	Single particle centroids (MeV)
$2s_{1/2}$	0	3·94	6	0·63
	1	1·76	2	2·31
$2p_{3/2}$	0	6·51	8	5·36
$1d_{3/2}$	0	7·10	8	2·27
	1	5·49	8	3·53
$1f_{7/2}$	0	8·13	16	4·37

experimental work is clearly required on this level as the theoretical calculations of Singh *et al* (1972) predict both a $J^\pi = 1^+$ and $J^\pi = 3^+$ level for which the 2·839 MeV level is the only available candidate in this region of excitation energy.

4.1.3. The 3·019, 3·731 and 4·468 MeV levels. The mixture of $l_p = 0$ and $l_p = 2$ components required to fit the angular distributions of the 3·019 and 3·731 MeV levels satisfactorily indicates $J^\pi = 1^+$ for both of the levels confirming previous assignments for the 3·019 MeV level and making a unique assignment to the 3·731 MeV level which is listed by Endt and van der Leun (1973) as $J^\pi = (1, 2^+)$.

The pure $l_p = 0$ angular distribution to the 4·468 MeV level indicates $J^\pi = (0, 1)^+$ consistent with a previous $J^\pi = 0^+$ assignment.

4.2. Levels excited with $l_p = 1$ transfer

Figure 3 shows the experimental angular distributions for the levels which have been excited by $l_p = 1$ transfers. The allowed J^π are $(0, 1, 2)^-$ but for the lower-lying levels $2p_{3/2}$ proton transfer is more probable than $2p_{1/2}$ transfer hence $J^\pi = 0^-$ is less likely than 1^- or 2^-.

4.2.1. The 3·927, 4·144 and 5·412 MeV levels. The work of Vermette *et al* (1968) shows that the anisotropy in the angular correlation of the 3·927 → 2·938 MeV γ ray transition rules out $J^\pi = 0^-$ while the present work rules out $J \geqslant 3$. From the lifetime, 125^{+20}_{-14} fs (Nolan *et al* 1972), together with the mixing ratios obtained for the 3·927 → 2·938 MeV transition for $J = 1$ and $J = 2$ hypotheses by Vermette *et al* (1968) the transition strengths for the M2 components of the transition are unacceptably large. A preliminary $^{28}Si(^3He, p\gamma)^{30}P$ angular correlation experiment carried out in this laboratory to check the mixing ratios obtained for the $J = 1$ and 2 hypotheses (Crossfield B E 1971, private communication) fitted the experimental angular correlation over a wider range of mixing ratios than allowed by Vermette *et al* (1968) and the $J = 1$ hypothesis could fit the data assuming a pure E1 transition. However, the $J = 2$ hypothesis while producing a wider range of mixing ratios still gave unacceptable M2 transition strengths. This suggests that $J^\pi = 1^-$ rather than 2^- is the more probable assignment for this level.

The present work restricts J^π to $(0, 1, 2)^-$ for the 4·144 MeV level which is consistent with a previous 2^- assignment to the level (Endt and van der Leun 1973).

No previous spin or parity assignments have been made to the 5·412 MeV level but the present work restricts J^π to $(0, 1, 2)^-$.

4.2.2. The 5·908 and 5·994 MeV levels. The present work restricts J^π for both levels to $(0, 1, 2)^-$ consistent with a previous $J = 1, 2$ restriction for the 5·908 MeV level and a $J = 1$ assignment for the 5·994 MeV level (Endt and van der Leun 1973).

4.3. Levels excited with $l_p = 2$ transfers

Figure 2 shows the experimental angular distributions which have been fitted assuming $l_p = 2$ transfer, the possible J^π assignments therefore being $(1, 2, 3)^+$, however $J^\pi = 3^+$ is less likely for these levels since the $1d_{5/2}$ shell should be largely filled.

4.3.1. The 1·454, 2·723 and 2·938 MeV levels. The present work is consistent with the J^π assignments of 2^+ made to all of these levels (Endt and van der Leun 1973).

4.3.2. The 3·834, 4·183 and 4·425 MeV levels. The 3·834 MeV level is listed as $J^\pi = (1, 2^+)$ in the review of Endt and van der Leun (1973), the present work is consistent with the J restriction and a positive parity assignment to the level.

Both the 4·183 and 4·425 MeV levels have $J^\pi = 2^+$ and the present work is consistent with these assignments.

4.3.3. The 4·501, 5·024, 5·504 and 5·598 MeV levels. The 4·501 MeV level is known to have $J^\pi = 1^+$ and the present work is consistent with that assignment.

The shape of the angular distribution leading to the 5·024 MeV level is very speculative due to poor statistical accuracy. No conclusions may be drawn from the present experiment but an $l_p = 2$ DWBA curve has been included in figure 2 to guide the eye.

No spin or parity assignments have been made previously to the 5·598 MeV level, the present work restricts J^π to $(1, 2, 3)^+$.

4.4. Levels excited with $l_p = 3$ transfers

Figure 3 shows the experimental angular distributions for the levels excited by $l_p = 3$ transfer. The allowed J^π are $(2, 3, 4)^-$ however, for lower-lying levels $1f_{7/2}$ proton transfer is more probable than $1f_{5/2}$ transfer, therefore $J^\pi = 3^-$ or 4^- are more likely than 2^-.

4.4.1. The 4·230 and 4·235 MeV levels. The doublet observed by Nolan *et al* (1972) at 4·230 and 4·235 MeV could not be resolved in the present work. However, the predominant shape of the angular distribution is $l_p = 3$ and J^π for the 4·230 MeV level is 4^- (Endt and van der Leun 1973). Lack of information on the spin or parity of the 4·235 MeV level means that the spectroscopic factor extracted in table 2 assuming that the $l_p = 3$ transfer proceeds wholly to the 4·230 MeV level should be viewed with caution.

4.4.2. The 4·625 and 4·921 MeV levels. The 4·625 MeV level is known to have $J^\pi = 3^-$ and the present work is consistent with this assignment.

The recent compilation of Endt and van der Leun (1973) lists $J^\pi = 5^-$ (3^-) for the 4·921 MeV level. The present work rules out a 5^- assignment and one therefore concludes that $J^\pi = 3^-$ for this level.

4.5. Other levels

4.5.1. The 4·343 and 4·734 MeV levels. These levels were weakly excited and the 4·734 MeV level was obscured by an impurity group at some angles in the present experiment hence no fits were attempted to the poor angular distributions obtained.

4.5.2. The 1·973 and 2·538 MeV levels. In this region of nuclear masses caution is necessary with respect to parity assignments and J restrictions based on angular distributions which are well fitted by $l_p = 3$ DWBA calculations when carrying out stripping reactions on odd mass nuclei. Figure 2 shows the angular distributions of the 1·973 and 2·538 MeV levels, both are fitted quite well by DWBA calculations assuming $l_p = 3$ transfer, however both have $J^\pi = 3^+$ (Endt and van der Leun 1973) which rules out the possibility of $l_p = 3$ transfer. Clearly the single step $l_p = 2$, $1d_{5/2}$ transfers also shown in figure 2 do not fit these angular distributions very well and this is the particle transfer one would expect in order to obtain $J^\pi = 3^+$ at such low excitation energies in this mass region. In view of the difficulties with the single step process a core excitation mechanism could well be required to explain the shapes of these angular distributions but the strength of these transitions is noteworthy when compared with the strength one usually associates with core excited states.

The poor fit of $l_p = 2$ calculations to angular distributions leading to final states of $J^\pi = 3^+$ may indicate that those levels which are well fitted by $l_p = 2$ calculations proceed by $1d_{3/2}$ proton transfer leading to final states of 1^+ or 2^+, in this event the 5·504 and 5·598 MeV levels may be restricted to $J^\pi = 1^+$ or 2^+. It should perhaps be emphasized that the shape difference between the angular distributions leading to the 3^+ states and the $l_p = 2$ distributions leading to other states is not a $l_p = 2, j$-dependent effect in the usual meaning of the term as seen in stripping with even–even targets. In the present case it is certainly not clear that the 3^+ states have been formed by a single step $1d_{5/2}$ transfer and in any event there are gross differences in the positions of the main stripping peaks which are not seen in the work of Mertens *et al* (1970) on j dependence in $l_p = 2$ transfers with even mass targets.

5. Discussion

The spectroscopic strengths $(2J_f + 1)S$ are listed in table 2 and compared with theoretical values calculated using Nilsson wavefunctions and compared with shell model calculations. The collective model calculations by B C Walsh (1970, private communication) assumed a proton captured to an oblate ($\beta = -0{\cdot}1$) ^{29}Si core as suggested by the work of Bromley *et al* (1967). The shell model calculations of Glaudemans *et al* (1964) assumed an inert ^{28}Si core with two-particle interactions in the $2s_{1/2}$ and $1d_{3/2}$ shells. It is clear from table 2 that neither of the model calculations describes the experimental spectroscopic data adequately and the presence of the two $J^\pi = 3^+$ states at 1·973 and 2·538 MeV showed the need to include the effects of $1d_{5/2}$ proton holes in shell model calculations which attempted to describe ^{30}P.

An attempt was made by Wildenthal *et al* (1971) to include two-particle interactions involving $1d_{5/2}$ holes in an extensive shell model fitting procedure to nuclei in the 2s–1d shell. The results also predicted spectroscopic factors for stripping and pick-up to many of the nuclei. The predictions refer only to positive-parity levels and the agreement between model energies and measured values is fairly good in ^{30}P up to about 3·5 MeV.

At about 3·5 MeV and 4·0 MeV are predicted levels of 5^+ and 4^+ respectively for which there are unfortunately no candidates available in the experimental level scheme of ^{30}P until 4·235 MeV (this is the lowest-lying level without a J^π assignment to date). Model predictions of ^{31}P neutron pick-up spectroscopic factors are roughly consistent with the experimentally determined numbers but no predictions are given for stripping reactions which might be compared with the present work. Restrictions imposed by the assumption of a truncated $1d_{5/2}$ configuration space in the calculations are expected to be felt more strongly for those nuclei with mass just greater than ^{28}Si than for those towards ^{40}Ca. However, truncated space or not results for odd–odd nuclei such as ^{30}P are consistently the least satisfactory for most shell model calculations although successive attempts show improvements.

Theoretical calculations on the low-lying structure of ^{30}P have been carried out using a modified version of the vibrational unified model by Singh *et al* (1972). The model was able to predict the main features (up to 3·5 MeV) of the experimental level scheme although as noted earlier (§ 4.1.2) it is not clear with which predicted level the 2·839 MeV level should be associated. It is particularly noteworthy that this model is capable of predicting three low-lying $J^\pi = 3^+$ states with the assumption of a closed $1d_{5/2}$ subshell and creates further interest in the mode of excitation of the 1·973 and 2·538 MeV $J^\pi = 3^+$ states observed with such strength in the present experiment.

No theoretical calculations have been carried out for the negative-parity states in ^{30}P but it is noteworthy in table 3 that much of the $2p_{3/2}$ and $1f_{7/2}$ strength has been observed in the present experiment (the measured values may contain some $2p_{1/2}$ and $1f_{5/2}$ strength respectively due to the difficulty in deciding whether $j = l_p + \frac{1}{2}$ or $l_p - \frac{1}{2}$ for the reaction).

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