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Study of energy levels of ^{29}Si via deuteron stripping

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Abstract. The ^{28}Si(d, p) ^{29}Si reaction has been studied at $E_d = 10$ MeV with a multigap magnetic spectrograph which can record 24 spectra at angles ranging from 5° to 175°. Eighty two proton groups have been identified as belonging to the ^{28}Si(d, p) reaction covering excitation energies in ^{29}Si up to 9·676 MeV. Angular distribution measurements on 61 proton groups corresponding to levels up to 9·154 MeV have been carried out and those exhibiting stripping patterns have been analysed. Spectroscopic factors for bound states have been derived using the finite range DWBA method with nonlocal correction FRNL.

1. Introduction

In recent years, considerable attention has been given to studying the level structure of the 1d–2s shell nuclei, especially that of ^{29}Si on account of its being in the middle of a region where nuclear deformation is changing from prolate to oblate. Experimentally, there is an indication that the ^{29}Si nucleus has a relatively weak oblate shape. However, no satisfactory reproduction of either such weakness of the oblate deformation or the level spectroscopic factors, has been achieved in terms of unmixed rotational bands based on deformed orbital Hartree–Fock calculations (Jones *et al* 1970, Mermaz *et al* 1969, 1971 and Ford *et al* 1971). Moreover, the simple shell model configuration describing the nucleus as a closed ^{28}Si core filling the $1d_{5/2}$ subshell, is in conflict with various experimental data (Dehnhard and Yntema 1970). These results strongly suggest some core excitation out of the $1d_{5/2}$ orbit besides revealing admixtures of $(2s_{1/2})^2$ and $(1d_{3/2})^2$ in the ground state of ^{28}Si. In the mass region $A = 30$–35 Wildenthal *et al* (1971) have reported shell model calculations using all Pauli-allowed basis vectors of possible $1d_{5/2}$, $2s_{1/2}$ and $1d_{3/2}$ configurations. Unfortunately, no calculations are yet available for $A = 29$ which is somewhat difficult since the number of possible configurations is relatively large near the middle of the shell. It is thus of interest to investigate the particle structure relative to that of the doubly even ^{28}Si core by adding a captured neutron via a ^{28}Si(d, p) ^{29}Si stripping reaction. Population of the ^{29}Si excited states by this direct reaction mechanism is of value in establishing the particle–hole components in ^{28}Si, moreover, accurate experimental spectroscopic information is needed for comparison with current model predictions as well as to stimulate further theoretical studies.

Earlier work on the spectroscopy of the ^{29}Si levels is summarized in the compilation of Endt and Van der Leun (1967) which includes an extensive analysis carried out by Browne and Radzyminski (1960) from (d, p) measurements, where it has been possible to report 65 proton groups corresponding to excited states in that nucleus up to 9·053 MeV. Spin and parity assignments of some of these states up to 6·4 MeV have been mainly determined from the momentum transfer characterizing the structure of the angular distributions of the outgoing particle groups (Holt and Marsham 1953, Alekseev *et al* 1960, Blaire and Quisenberry 1961, Wildenthal *et al* 1964 and Betigeri *et al* 1966). Recently, Mermaz *et al* (1971) have reported at E_d = 18–21 MeV, forward-angle (d, p) angular distributions for 14 levels in ^{29}Si with experimental proton energy resolution of 60 keV. Moreover, several experiments have been recently performed applying various appropriate reactions, in particular that of $^{27}Al(^{3}He, p)^{29}Si$ (Meyer-Schutzmeister *et al* 1969), $^{30}Si(^{3}He, \alpha)^{29}Si$ (Dehnhard and Yntema 1970) as well as the $^{26}Mg(\alpha, n\gamma)^{29}Si$ reaction (Bardin *et al* 1971).

Although there is general agreement between the previously reported results, still a few discrepancies are noted in some energy level locations and l_n assignments. Moreover, most authors confined their (d, p) measurements to the forward angles and limited their analysis to PWBA calculations.

The aim of the present work is not only to extend the investigation with better resolution to higher excited states but also to carry out angular distribution measurements covering nearly the whole angular range besides applying DWBA calculations in determining the l_n values and spectroscopic factors for bound states.

2. Experimental procedure and measurement

Deuterons accelerated to 10 MeV by the Aldermaston tandem Van de Graaff generator were allowed to enter the target chamber of a multigap magnetic spectrograph designed by Middleton and Hinds (1962). A thin foil of natural SiO_2 evaporated onto a carbon backing was used. The outgoing protons were momentum analysed at angular intervals of 7·5° over an angular range 5°–175° and detected by 24 nuclear emulsion plates each of 40 in, placed along the corresponding focal planes of the magnets within the spectrograph. The variation of the solid angle of incidence of the particles upon the surface of the photographic emulsion has been estimated and a correction for the group intensity has been applied. To simplify the scanning process, absorbers of thin polythene of 0·01 in thickness were placed in contact with the photoemulsion to stop scattered deuterons. However, such filters have limited the measurements of low energy protons to those having energies greater than about 5·5 MeV. The overall energy resolution was found to be better than 15 keV FWHM. Scanning and analysis of these emulsion plates have been carried out at Ein Shams University, Cairo and a typical proton spectrum recorded at an angle of 107·5° is presented in figure 1. It has been found that the observed proton groups belong mainly to the most abundant ^{28}Si isotope (92·28 %) and the other major target constituents, that is ^{12}C and ^{16}O nuclei. The detected weak background could be attributed to the other silicon isotopes as well as other target contamination nuclei. The proton groups corresponding to ^{29}Si energy levels are denoted by numbers starting from zero for the ground state while groups from other target nuclei are represented by the corresponding chemical symbol of the residual nuclei with a subscript indicating the appropriate state.

3. Energy level analysis

As shown in figure 1, it was possible to assign 82 proton groups to the $^{28}Si(d, p)^{29}Si$ reaction covering excitation energies in ^{29}Si up to 9·676 MeV as listed in table 2. The

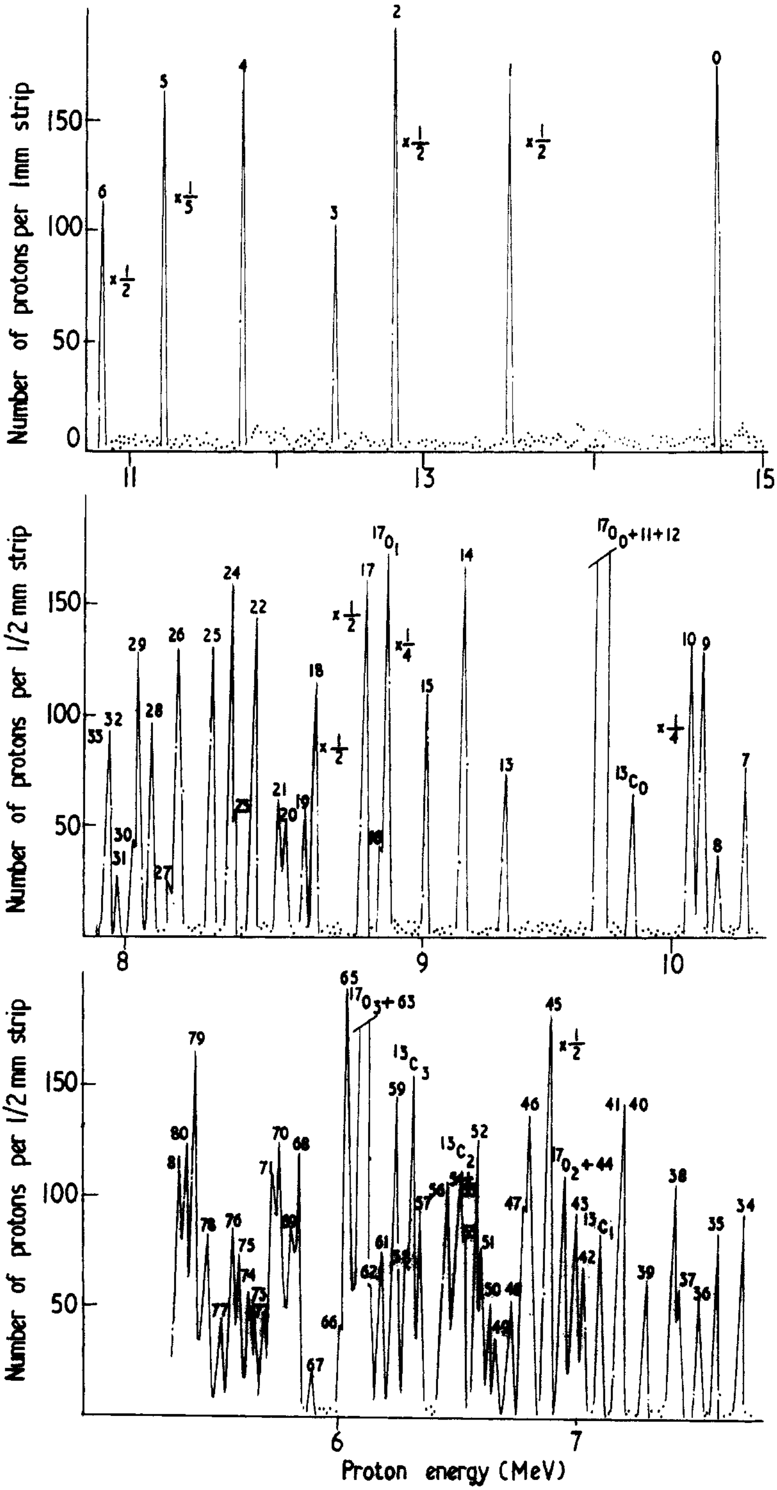

Figure 1. Typical proton spectrum recorded at an angle of 107·5° for the $^{28}Si(d, p)^{29}Si$ reaction at $E_d = 10$ MeV.

reaction energy Q_0 is found to be $6{\cdot}244 \pm 0{\cdot}007$ MeV in excellent agreement with the value of $6{\cdot}246 \pm 0{\cdot}010$ MeV reported by Van Patter and Buechner (1952) as well as the value of $6{\cdot}251 \pm 0{\cdot}004$ MeV derived on the basis of the mass difference table given by Endt and Van der Leun (1967). With regard to the excitation energies, the present investigation has identified 81 excited states in ^{29}Si. In comparison with previous data one has to point out the following remarks.

(i) The excited states at 8·641 and $9{\cdot}012 \pm 0{\cdot}007$ MeV confirm the uncertain levels previously reported (Browne and Radzyminski 1960) at 8·644 and 9·013 MeV.

(ii) The excited state at $8{\cdot}966 \pm 0{\cdot}007$ MeV in addition to 15 higher levels with energies ranging from 9·154 to $9{\cdot}697 \pm 0{\cdot}012$ MeV are considered to be new. Some of these states are supported by previous results from other reactions. The ^{31}P(d, α)^{29}Si reaction (Curry *et al* 1969) shows a level at 9·358 MeV which corresponds to the present level at 9·349 MeV. Also from neutron resonances on silicon (Frier *et al* 1950) excitation energies of the compound nucleus ^{29}Si at 9·261, 9·424 and 9·664 MeV are in agreement with the present levels at 9·256, 9·423 and 9·670 MeV respectively. The latter level has been recently reported from (^{3}He, α) measurements (Dehnhard and Yntema 1970).

4. Proton angular distributions

Measurements have also been carried out on the angular distribution of various proton groups belonging to 61 excited states in ^{29}Si up to an excitation energy of 9·154 MeV. About 60% of these distributions are found to exhibit stripping patterns and trials have been made to obtain their best fit with the appropriate theoretical angular distribution curves. DWBA calculations for the bound states have been performed using a program of Smith (1967) after being adjusted to run on the ICL 1905E computer at Cairo University. For calculating the distorted waves of the incoming deuterons and the outgoing protons, the optical model parameters adopted in the present investigation are those successfully used by Smith (1969) at $E_d = 10$ MeV (table 1). The real potential depth for each proton group of energy E was calculated using its linear energy dependence formula, $V_0 = 56{\cdot}05 - 0{\cdot}55\,E$ (Perey 1963).

It should be noted that the captured neutron was assumed to be bound in a real well having a Woods–Saxon form of the standard geometry: $r_0 = 1{\cdot}25$ fm; $a_0 = 0{\cdot}65$ fm

Table 1. Optical model parameters used in the DWBA analysis

$$U(r) = U_c(r) - V_0(1+e^x)^{-1} - iW_0(1+e^{x'})^{-1}$$

$$U_c = \left(\frac{Ze^2}{2r_{0c}A^{1/3}}\right)\left\{3 - \left(\frac{r}{r_{0c}A^{1/3}}\right)^2\right\} \qquad r < r_{0c}A^{1/3}$$

$$U_c = \frac{Ze^2}{r} \qquad r > r_{0c}A^{1/3}$$

$$x = \frac{r - r_0A^{1/3}}{a} \qquad x' = \frac{r - r_0'A^{1/3}}{a'}$$

	V_0	r_0	a	W_0	r_0'	a'
Deuteron parameters	101·1	1·15	0·823	20·6	1·54	0·45
Proton parameters	47·1	1·25	0·650	7·7	1·25	0·47
Neutron bound state parameters		1·25	0·650			

and spin–orbit depth of 6 MeV. The potential depth was adjusted to give the correct neutron binding energy. The adoption of these parameters together with the exclusion of a spin–orbit term in both proton and deuteron potentials have been found, from initial tests, to be acceptable.

To reduce the contribution from the nuclear interior, the DWBA calculations were carried out using the finite range and nonlocal corrections (FRNL). For this purpose, the Hulthen finite range proton–neutron interaction with a second order approximation was used together with a range of nonlocality of 0·85 fm for protons or neutrons and 0·54 fm for deuterons (Perey and Buck 1962).

A summary of the results of the DWBA analysis for the bound states in ^{29}Si is shown in table 2. The absolute spectroscopic factor S_J for each of these states has been obtained by normalizing the calculated cross sections at forward angles around the principal maximum, to the corresponding experimental data in absolute units. The relation describing the one nucleon transfer to the 0^+ target nucleus forming a residual nucleus in a state of spin J is as follows:

$$\sigma_{\exp} = (2J+1)S\sigma_{\text{theo}}.$$

It should be noted that the experimental angular distributions are presented in the same arbitrary units and could be converted to millibarns per steradian by multiplying by a factor of $7{\cdot}1\times10^{-4}\pm20\%$. The latter was derived through normalizing the present experimental data for the ground state transition at forward angles with the corresponding values measured in absolute units at $E_d = 10$ MeV by Goss (1964, as quoted by Smith 1969). For discussing the results concerning the various observed angular distributions, a classification based on the value of the orbital angular momentum transfer is given in the following sections.

4.1. The $l_n = 0$ transitions

Angular distributions for proton groups corresponding to the ground state and 4·830 MeV excitation energy are found, as shown in figure 2, to be characterized by $l_n = 0$, thus

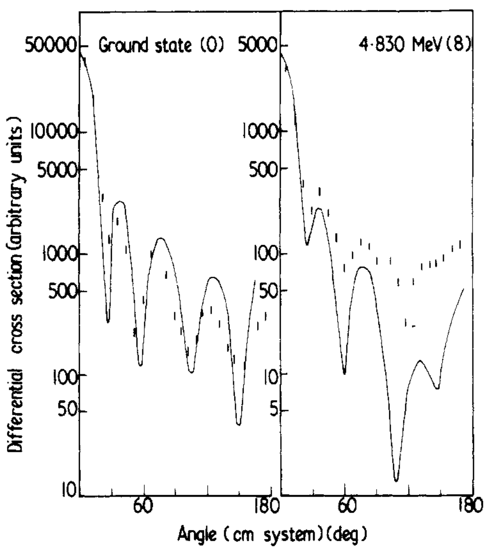

Figure 2. Angular distributions for $l_n = 0$ transitions.

indicating that each of these states should have $J^\pi = \frac{1}{2}^+$. The present strong $l_n = 0$ transition to the $\frac{1}{2}^+$ ground state has been also noted in both (d, p) stripping (Mermaz *et al* 1971) as well as ^{30}Si(d, t) (Dehnhard and Yntema 1970) reactions, and accordingly this state is dominantly populated by a $2s_{1/2}$ single-particle component. The $\frac{1}{2}^+$ assignment for the other state at 4·830 MeV is in agreement with that reported from ^{27}Al(^{3}He, p) (Meyer-Schutzmeister *et al* 1969) and ^{30}Si(^{3}He, α) (Dehnhard and Yntema 1970) reactions. Moreover, the relatively weak transition to this state is consistent with the small proton width reported by Ejiri *et al* (1964) for the analogous $\frac{1}{2}^+$ state at 4·761 MeV in the mirror nucleus ^{29}P. Accordingly this $\frac{1}{2}^+$ state cannot be considered as the second member of the $k^\pi = \frac{1}{2}^+$ rotational band on Nilsson orbit 11 as proposed by Main *et al* (1970) but may be the base of that band.

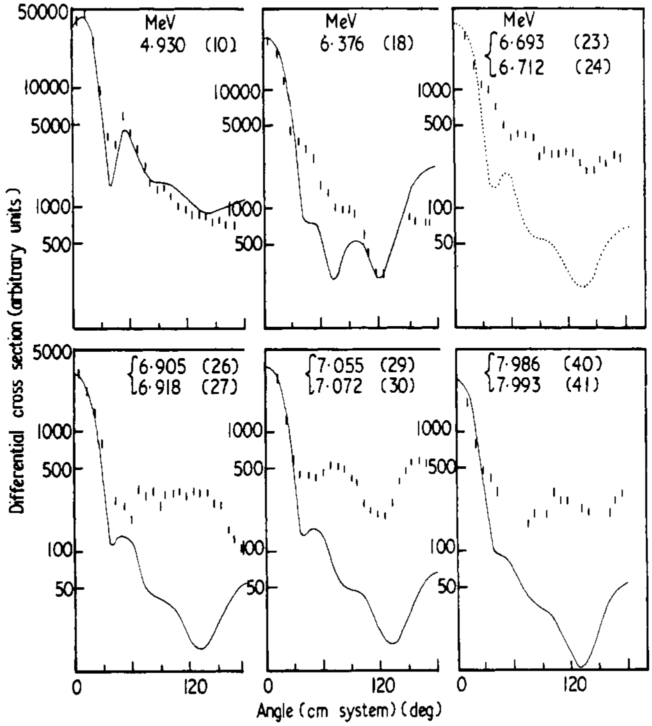

Figure 3. Angular distributions for $l_n = 1$ transitions.

4.2. The $l_n = 1$ transitions

Two proton groups corresponding to energy levels at 4·930 and 6·376 MeV and four doublets belonging to higher excited states are found to have angular distributions characterized by $l_n = 1$ as shown in figure 3. Such assignment for the two lower excited states is in agreement with previous (d, p) stripping investigations but no data concerning the other upper states have yet been reported. The present assignment indicates that the concerned levels have negative parity and a spin $\frac{1}{2}$ or $\frac{3}{2}$. From cascade studies of γ radiation following thermal neutron capture in silicon, Manning and Bartholomew (1959) reported strong dipole γ rays to the 4·930 and 6·376 MeV states which are found to have J values of $\frac{3}{2}^-$ and $\frac{1}{2}^-$ respectively. Moreover, these states are excited quite strongly and could be thus interpreted as the major components of the $2p_{3/2}$ and $2p_{1/2}$ single particle states, respectively. Such behaviour is supported by the data recently reported at $E_d = 21$ MeV by Mermaz *et al* (1971) but, although their spectroscopic factor for the $\frac{3}{2}^-$ level at 4·930 MeV is 0·55 in excellent agreement with the present value, yet, for the $\frac{1}{2}^-$ state at 6·376 MeV their value of 0·53 is larger than that obtained in the present experiment.

4.3. The $l_n = 2$ transitions

Eighteen proton groups and two doublets belonging to different excited states of energies ranging from 1·275 MeV to 9·154 MeV are found to have angular distributions of $l_n = 2$ as shown by the DWBA curves for the bound states (figure 4) and the PWBA curves for the higher excited states (figure 5). Each of the concerned levels should have even parity and spin $\frac{3}{2}$ or $\frac{5}{2}$.

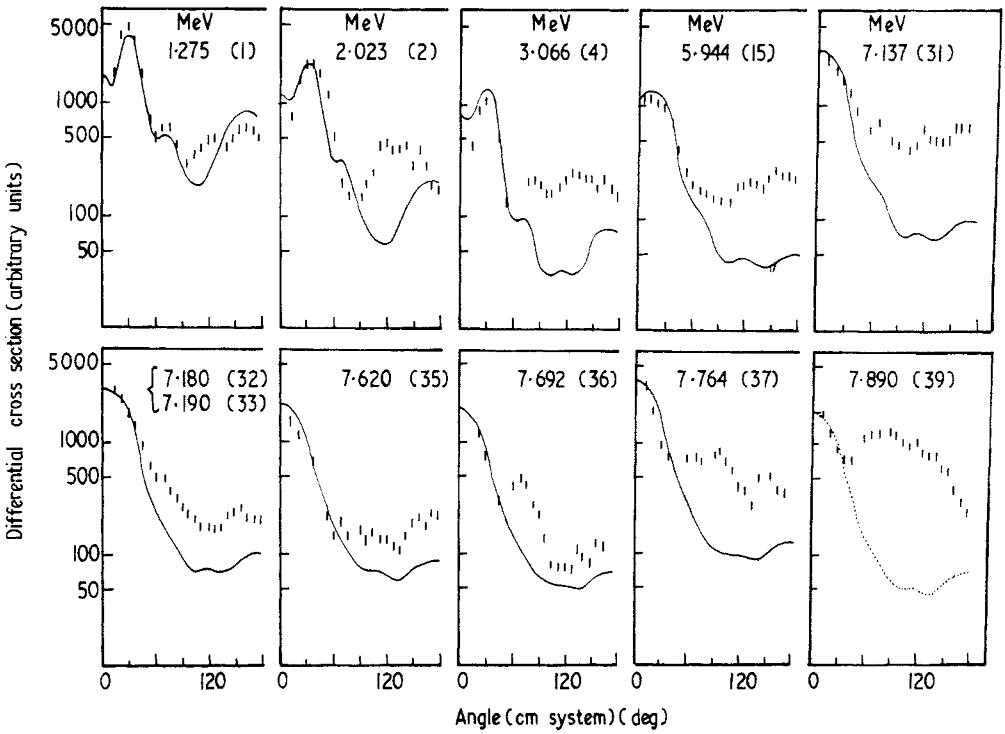

Figure 4. Angular distributions for $l_n = 2$ transitions to bound states.

Definite spin assignments could be established for the three low lying excited levels at 1·275, 2·023 and 3·066 MeV as $\frac{3}{2}^+$, $\frac{5}{2}^+$ and $\frac{3}{2}^+$, respectively on account of the results reported by Becker *et al* (1967) from γ angular correlation measurements arising from ^{29}Si states populated by the ^{28}Si(d, p) reaction. Such assignments are in accordance with those reported by Ejiri *et al* (1964) for the analogous levels in the mirror nucleus ^{29}P at 1·381, 1·96 and 3·102 MeV, respectively. Moreover, a spin assignment of $\frac{3}{2}^+$ for the excited state at 5·944 MeV in ^{29}Si could be favoured on account of the recent studies of γ radiations from the levels populated with the $^{26}Mg(\alpha, n)$ reaction (Bardin *et al* 1971).

In comparing the spectroscopic factors for these four states with those reported at $E_d = 18$ and 21 MeV by Mermaz *et al* (1971), reasonable agreement is shown for the $\frac{3}{2}^+$ states but the present values for the $\frac{5}{2}^+$ states are somewhat larger. However, the transition to the 1·275 MeV state is noted to have a large spectroscopic strength which amounts to 75% of the total $1d_{3/2}$ single particle strength.

The $l_n = 2$ transitions for the other higher excited states are considered to be new and in general they are relatively weak. In comparison with the results reported by Dehnhard and Yntema (1970) from the pick-up reaction $^{30}Si(^3He, \alpha)$, $l_n = 2$ transitions

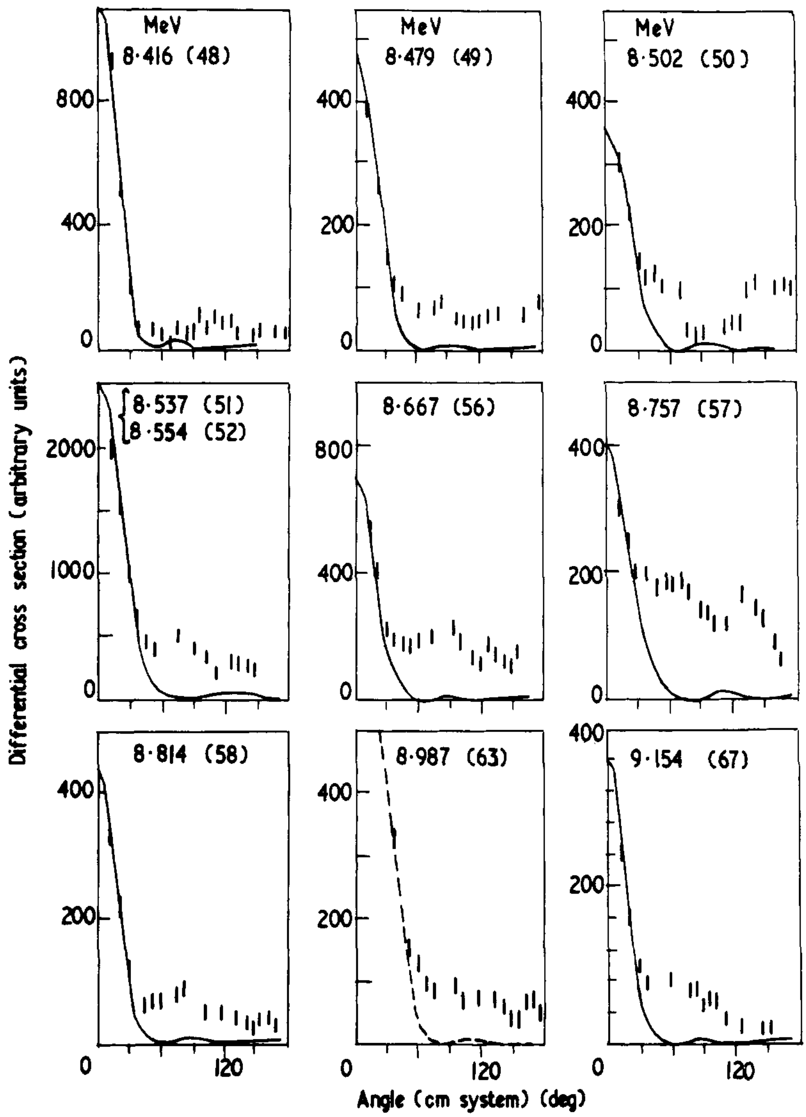

Figure 5. Angular distributions for $l_n = 2$ transitions to unbound states (PWBA analysis).

have been observed to states 7·21, 7·79 and 8·32 MeV in agreement with the present assignment for states at 7·180+7·190, 7·764 and 8·331 MeV. The latter state has been observed as a weak $l_n = 2$ (figure 7) component closely spaced with a strongly excited $l_n = 4$ level at 8·345 MeV as being analysed from the doublet angular distribution and gaussian fitting, at various angles of observations, for each group in the doublet. It is to be noted that, since the 8·331 MeV level is the isobaric analogue for the $\frac{5}{2}^+$ ground state in ^{29}Al, then it represents the lowest $T = \frac{3}{2}$ level having spin $\frac{5}{2}^+$.

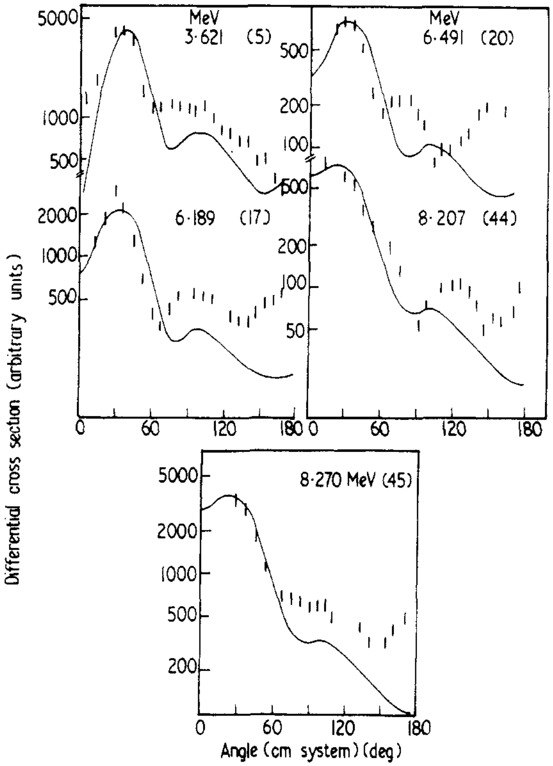

Figure 6. Angular distributions for $l_n = 3$ transitions.

4.4. *The $l_n = 3$ transitions*

Five proton groups corresponding to excitation energies 3·621, 6·189, 6·491, 8·207 and 8·270 MeV are found to have angular distributions characterized by $l_n = 3$ as shown in figure 6 thus indicating that each of these states should have odd parity and spin $\frac{5}{2}$ or $\frac{7}{2}$. The strong excitation of the 3·621 MeV state whose spin is established as $\frac{7}{2}^-$ on account of the γ correlation measurements reported by Becker *et al* (1967) can indicate that it is populated with a large fraction of $1f_{7/2}$ single-particle strength. Another level of relatively high transition strength is observed at 6·189 MeV and its spin is more likely to be $\frac{5}{2}^-$ from shell model considerations. It should be also noted that, among the remaining levels whose present assignments are considered to be new, a level at 8·270 MeV is found to have a spectroscopic factor nearly as high as that estimated for the 6·189 MeV state. Since the sum of the spectroscopic factors for states of certain J should be kept within $\Sigma_i S_J^i = 1$ as required by the stripping sum rule, then the large spectroscopic factor (0·88) extracted for the $\frac{7}{2}^-$ state at 3·621 MeV may suggest a spin of $\frac{5}{2}^-$ for the 6·189 and 8·270 MeV states.

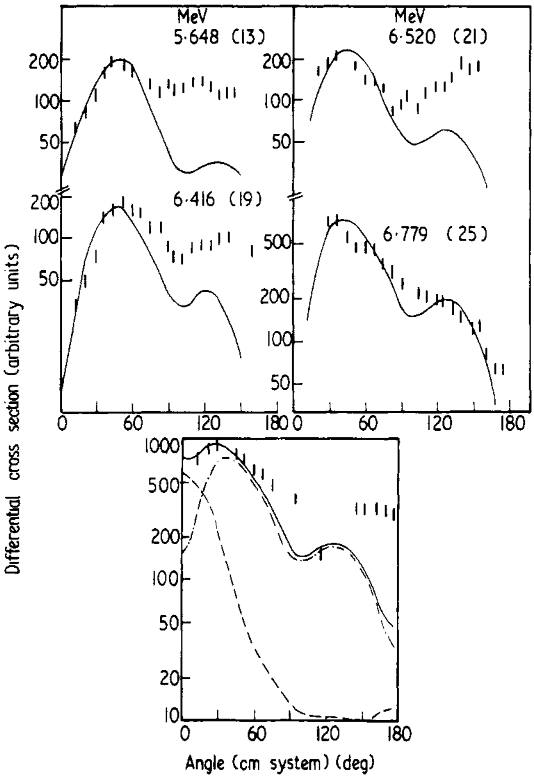

Figure 7. Angular distributions for $l_n = 4$ transitions. In the bottom diagram: full curve for $l_n = 2$ plus $l_n = 4$; broken curve: $E_x = 8{\cdot}331$ MeV (level number 46), $l_n = 2$; chain curve: $E_x = 8{\cdot}345$ MeV (level number 47), $l_n = 4$.

4.5. The $l_n = 4$ transitions

The (d, p) angular distributions for the five energy levels at 5·648, 6·416, 6·520, 6·779 and 8·345 MeV are found as shown in figure 7 to be characterized with $l_n = 4$. The assignment for the latter state has been obtained from the analysis of the doublet angular distribution, and that for the 6·779 MeV state is in agreement with the recent work of Mermaz *et al* (1971). Moreover, no definite spin assignment for any of these states has been previously reported except a tentative spin value of $\frac{1}{2}^+$ for a 5·660 MeV state (Meyer-Schutzmeister *et al* 1969) as well as for a 6·44 MeV state (Dehnhard and Yntema 1970) in contradiction to the present assignment for the corresponding states at 5·648 and 6·461 MeV. However, a spin of $\frac{5}{2}$ or $\frac{9}{2}$ has been recently reported for the former state from an investigation of the ^{26}Mg(α, nγ) reaction (Bardin *et al* 1971). Accordingly the assignment of $l_n = 4$ transition to this state can indicate that it might favourably have a spin of $\frac{9}{2}^+$ in support of that reported from the lifetime limit of that level as measured by Bailey *et al* (1972). It should be also noted that, the relatively high spectroscopic factor for the 6·779 MeV state indicates that it contains a large component of the $1g_{9/2}$ single-particle strength.

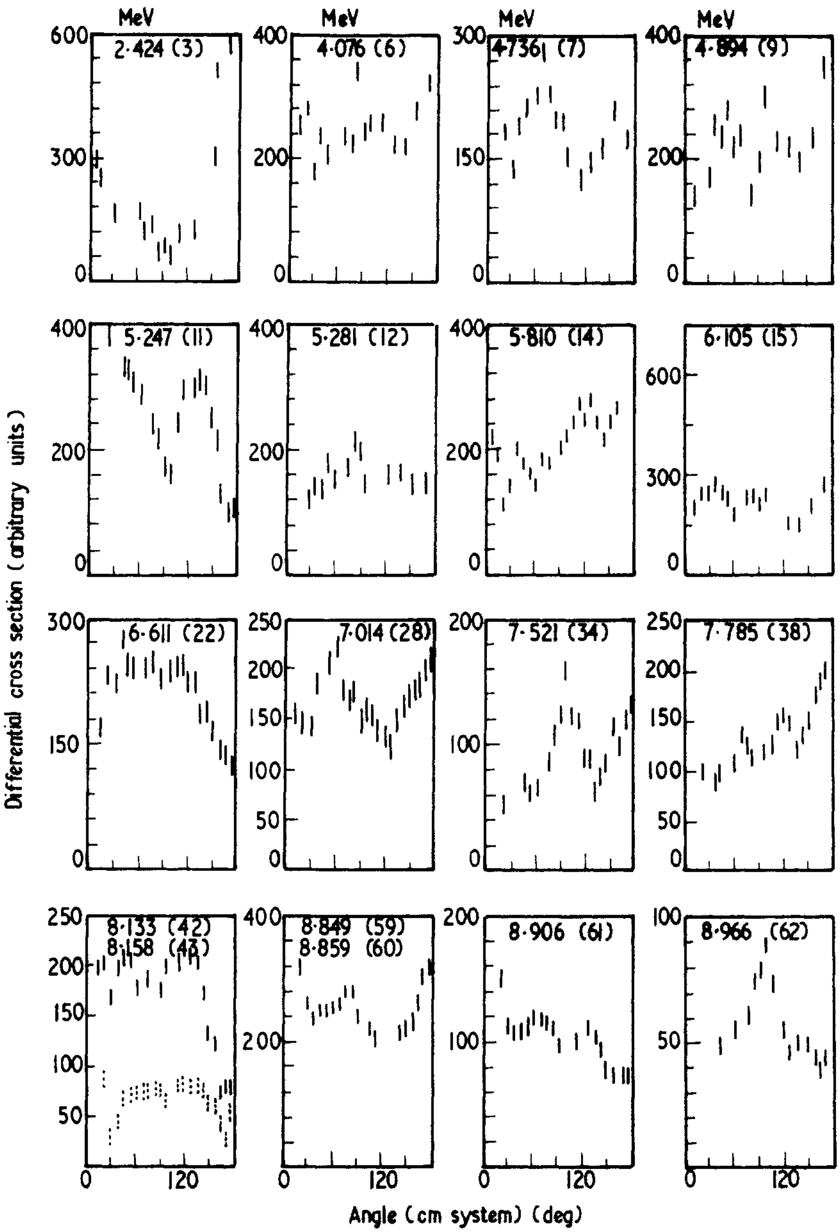

Figure 8. Angular distributions for levels exhibiting nonstripping patterns. In the distribution at the bottom left the results given by dotted vertical rules refer to the 8·133 MeV level while those given by full verticals refer to the 8·158 MeV level.

4.6. Levels exhibiting nonstripping patterns

Sixteen proton groups and one doublet corresponding to generally weak excited states of energies in the range 2–9 MeV have been found to show nonstripping patterns for their angular distributions as shown in figure 8. The majority of these distributions exhibit good isotropic behaviour or may be followed by intensity decrease at backward angles. Among these isotropic distributions one has to comment on the 4·076 MeV state on account of it being the analogue to the level at 4·082 MeV in the mirror nucleus ^{29}P, which is reported to have a probable spin of $\frac{7}{2}^+$ (Ejiri *et al* 1964). The spin of this state is recently suggested as $\frac{7}{2}$ from the (α, nγ) reaction (Bardin *et al* 1971). Previous (d, p) investigations (Endt and Van der Leun 1967 and Mermaz *et al* 1971) have shown a similar isotropic nature and no excitation for this state has been found in the case of (d, t) and (^{3}He, α) pick-up reactions (Dehnhard and Yntema 1970).

Besides this isotropic behaviour, four proton groups corresponding to states at 4·736, 5·247, 7·014 and 7·521 MeV are found to have angular distributions of sinusoidal patterns. Two other groups corresponding to states at 2·424 and 7·785 MeV are found to have distributions characterized by a considerable backward maximum twice as strong as its forward one. The spin of the former level has been established as $\frac{3}{2}^+$ from various experiments such as $^{29}P(\beta^+)^{29}Si$ decay (Roderick *et al* 1955) and γ correlation measurements (Becker *et al* 1967) as well as a neutron pick-up reaction on ^{30}Si (Dehnhard

Table 2. Angular momentum transfer and spectroscopic factors for levels observed in the $^{28}Si(d, p)\,^{28}(Si)$ reaction

Level number	E_x†	l_n‡	J§	S_{abs}
0	0	0	$\frac{1}{2}^+$	0·37
1	1·275	2	$\frac{3}{2}^+$	0·75
2	2·023	2	$\frac{5}{2}^+$	0·29
3	2·424	ns		
4	3·066	2	$\frac{5}{2}^+$	0·10
5	3·621	3	$\frac{7}{2}^-$	0·88
6	4·076	ns		
7	4·736	ns		
8	4·830	0	$\frac{1}{2}^+$	0·02
9	4·894	ns		
10	4·930	1	$\frac{3}{2}^-$	0·55
11	5·247	ns		
12	5·281	ns		
13	5·648	4	$\frac{7}{2}^+$ $\frac{9}{2}^+$§	0·16 0·13
14	5·810	ns		
15	5·944	2	$\frac{3}{2}^+$§ $\frac{5}{2}^+$	0·07 0·06
16	6·105	ns		
17	6·189	3	$\frac{5}{2}^-$§ $\frac{7}{2}^-$	0·37 0·30
18	6·376	1	$\frac{1}{2}^-$	0·26
19	6·416	4	$\frac{7}{2}^+$ $\frac{9}{2}^+$	0·07 0·06
20	6·491	3	$\frac{5}{2}^-$ $\frac{7}{2}^-$	0·12 0·10
21	6·520	4	$\frac{7}{2}^+$ $\frac{9}{2}^+$	0·16 0·13
22	6·611	ns		
23+24	6·693 6·712	(1)	$\frac{1}{2}^-$ $\frac{3}{2}^-$	0·03 0·02
25	6·779	4	$\frac{7}{2}^+$ $\frac{9}{2}^+$§	0·35 0·29
26+27	6·905 6·918	1	$\frac{1}{2}^-$ $\frac{3}{2}^-$	0·024 0·021

Table 2—continued

Level number	E_x†	l_n‡	J^π§	S_{abs}
28	7·014	ns		
29 + 30	7·055 } 7·072 }	1	$\frac{1}{2}^-$ $\frac{3}{2}^-$	0·026 0·023
31	7·137	2	$\frac{3}{2}^+$ $\frac{5}{2}^+$	0·011 0·009
32 + 33	7·180 } 7·190 }	2	$\frac{3}{2}^+$ $\frac{5}{2}^+$	0·11 0·09
34	7·521	ns		
35	7·620	2	$\frac{3}{2}^+$ $\frac{5}{2}^+$	0·042 0·036
36	7·692	2	$\frac{3}{2}^+$ $\frac{5}{2}^+$	0·037 0·031
37	7·764	2	$\frac{3}{2}^+$ $\frac{5}{2}^+$	0·006 0·005
38	7·785	ns		
39	7·890	(2)	$\frac{3}{2}^+$ $\frac{5}{2}^+$	0·003 0·002
40 + 41	7·986 } 7·993 }	1	$\frac{1}{2}^-$ $\frac{3}{2}^-$	0·018 0·016
42	8·133	ns		
43	8·158	ns		
44	8·207	3	$\frac{5}{2}^-$ $\frac{7}{2}^-$	0·07 0·06
45	8·270	3	$\frac{5}{2}^-$§ $\frac{7}{2}^-$	0·35 0·29
46	8·331 }	2	$\frac{3}{2}^+$ $\frac{5}{2}^+ : T = \frac{3}{2}$§	0·012 0·010
+	}			
47	8·345 }	4	$\frac{7}{2}^+$ $\frac{9}{2}^+$	0·22 0·19

Level number	E_x†	Level number	E_x†	Level number	E_x†
48	8·416‖	59 + 60	8·849 } 8·859 } ns	71	9·319
49	8·479‖	61	8·906 ns	72	9·349
50	8·502‖	62	8·966 ns	73	9·397
51 + 52	8·537 } 8·554 } ‖	63	8·987‖	74	9·423
53 + 54	8·600 } 8·608 }	64	9·012	75	9·467
55	8·641	65	9·039	76	9·485
56	8·667‖	66	9·054	77	9·527
57	8·757‖	67	9·154‖	78	9·579
58	8·814‖	68	9·224	79	9·638
		69	9·256	80	9·670
		70	9·300	81	9·697

† The estimated uncertainty in excitation energies (E_x) is 7 keV for levels up to 9·054 MeV and 12 keV for upper levels.
‡ Uncertain values are indicated in parentheses; ns refers to nonstripping.
§ Established or most favourable spin assignment (as discussed in text).
‖ $l_n = 2$ transitions (PWBA analysis).

and Yntema 1970). Trials have been made to fit the forward distribution with an $l_n = 2$ theoretical curve but it does not seem to be satisfactory. It is of interest to point out that such a pronounced backward feature has also been observed by El-Bedewi *et al* (1964) for the $\frac{3}{2}^+$ state at 0·098 MeV in ^{19}O. Therefore it is encouraging to develop an appropriate mechanism such as heavy particle stripping or exchange process to account for this effect.

5. Spectroscopic factor analysis

The (d, p) spectroscopic factors derived from the present DWBA analysis for transitions to bound states in ^{29}Si indicate that transitions to the low lying levels possess most of the total 2s–1d shell spectroscopic strength. Accordingly no rapid change in nuclear shape is expected in support of the results reported by Mermaz *et al* (1971). Moreover, the present experimental data ensure a considerable contribution of ^{28}Si core excitation as shown by the $\frac{5}{2}^+$ state at 2·023 MeV characterized by a spectroscopic factor of value comparable to that of the $\frac{1}{2}^+$ ground state besides the estimation of a total value of 0·39 for the summation of the spectroscopic factors for the $\frac{1}{2}^+$ transitions which are much lower than that expected from the stripping sum rule. It is thus clear that the independent particle shell model prediction for the closure of the $1d_{5/2}$ shell in ^{28}Si is no longer valid and the present results indicate that this orbit is neutron-filled by about 60% in agreement with that experimentally determined from the $^{28}Si(^3He, \alpha)$ reaction by Bray and Nurzynski (1969) as well as that theoretically derived from projected Hartree–Fock calculations (Castel *et al* 1970).

Table 3. Summed transition strengths for bound states in ^{29}Si

Transition	$\Sigma(2J+1)S$		Simple shell model predictions
	Present work $E_d = 10$ MeV	Mermaz *et al* (1971) $E_d = 18$ MeV	
2s–1d	7·39	5·3	6
1f	12·78	6·2	14
2p	3·00	3·3	6
1g	7·33	—	18

A comparison between the summed spectroscopic strengths measured at $E_d = 10$ MeV in the present investigation for 2s–1d, 1f, 2p and 1g transitions are shown in table 3, together with those reported at $E_d = 18$ MeV by Mermaz *et al* (1971) as well as those predicted by the simple shell model. Reasonable agreement between these results is noted within ±20% error for the summed 2s–1d spectroscopic strengths. It could be also noted that the present experiment has located within the bound states in ^{29}Si, almost (90%) all of the total 1f spectroscopic strength, but seems only to locate 50% and 41% of the total 2p and 1g spectroscopic strengths, respectively.

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