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(p,d) Reactions on Silicon Isotopes at 27.3 MeV

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The neutron pick-up reactions $^{29}Si(p, d)^{28}Si$ and $^{30}Si(p, d)^{29}Si$ have been studied at a bombarding proton energy of 27.3 MeV. Several angular distributions were analyzed with the distorted-wave Born approximation and the resulting spectroscopic factors and sum rule are given. The results indicate that the neutron configuration of the silicon isotopes contains $1d_{5/2}$, $2s_{1/2}$, and $1d_{3/2}$ components. A small f-wave neutron component has been found in ^{30}Si. Strong $d_{5/2}$ transitions have been observed to the unresolved doublet ($J^\pi = 3^+, 2^+; T=1$) at 9.32 MeV in ^{28}Si and to the ($J^\pi = \frac{5}{2}^+; T=\frac{3}{2}$) level at 8.32 MeV in ^{29}Si. These states are the isobaric analogs to the states of ^{28}Al (0 and 0.031 MeV) and to the ground state of ^{29}Al, respectively. The $J^\pi = 4^+$ state at 4.61 MeV in ^{28}Si was excited in the $^{29}Si(p, d)^{28}Si$ reaction, indicating target excitation effects in single-nucleon-transfer reactions.

I. INTRODUCTION

Nuclei in the $2s$-$1d$ shell have received considerable attention in recent years. Glaudemans, Wiechers, and Brussaard[1] performed a shell-model calculation assuming that ^{28}Si forms an inert core filling the $d_{5/2}$ shell. This assumption turns out not to be in agreement with the experimental information about the ^{28}Si nucleus. Several experiments[2-6] performed using $(^3He, \alpha)$, (p,d), and (d,t) reactions have shown appreciable core excitation. More recently, attempts have been made[7] to include many more nucleon configurations within the $d_{5/2}$-$s_{1/2}$-$d_{3/2}$ shell.

The (p,d) reaction on silicon isotopes has been reported[8] only for ^{28}Si at bombarding energies between 27.6 and 155 MeV. In order to complete the study of the ground-state structure of the silicon isotopes by (p,d) reactions, the present experiment was performed on ^{29}Si and ^{30}Si nuclei at 27.3 MeV. In addition, it seemed interesting to investigate whether the 4^+ state at 4.61 MeV of ^{28}Si is excited by the (p,d) reaction. The excitation of this state in a direct pick-up process should involve the transfer of a g-wave neutron. Recently,[9,10] it has been proposed that these levels are not excited by simple nucleon transfer but by a multiple-excitation process.

II. EXPERIMENTAL PROCEDURE

The Milano azimuthally-varying-field cyclotron provided the source of a 27.3-MeV proton beam. The beam-energy spread was about 230 keV. The ^{29}Si and ^{30}Si targets were produced by vacuum evaporation of enriched SiO_2 ($^{29}SiO_2$ enriched to 92%, $^{30}SiO_2$ enriched to 95.5%) on a thin carbon backing. The target thickness was estimated by a comparison with the elastic scattering of 3-MeV α particles from the C.N. Van de Graaff accelerator of Legnaro (Padova). Under the assumption that the elastic scattering at these lower energies is well

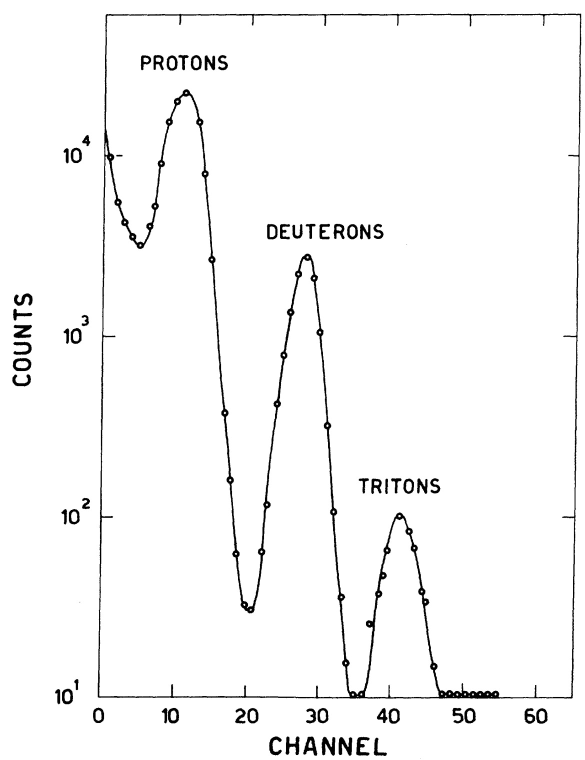

FIG. 1. Mass-identifier-output spectrum for the $Z=1$ reaction products.

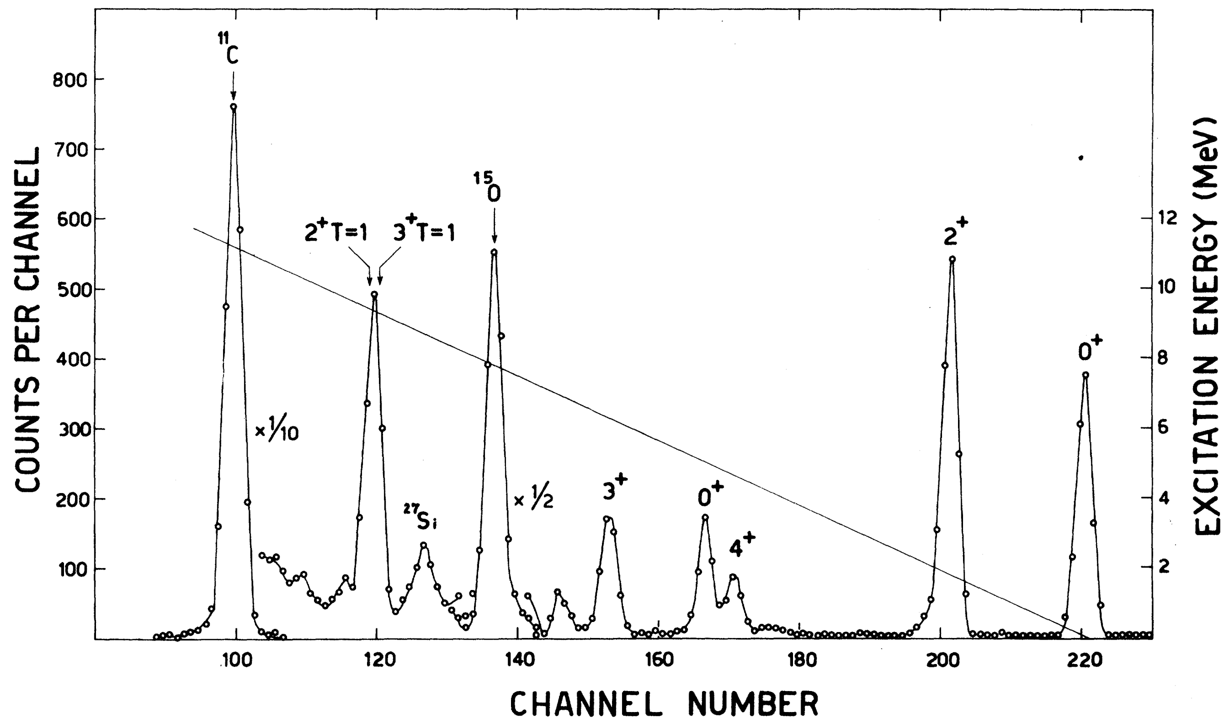

FIG. 2. Deuteron spectrum from the $^{29}Si(p,d)^{28}Si$ reaction at $\theta_{lab} = 50°$. The straight line gives the excitation energy of the residual ^{28}Si nucleus.

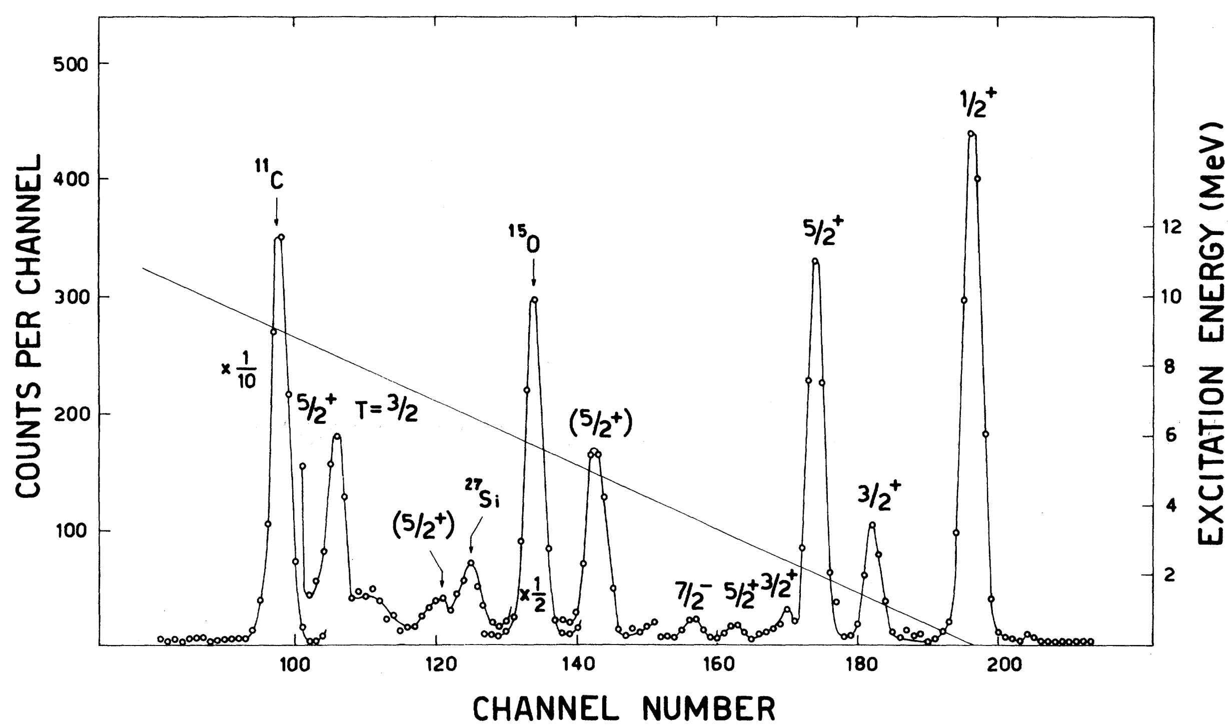

FIG. 3. Deuteron spectrum from the $^{30}Si(p,d)^{29}Si$ reaction at $\theta_{lab} = 50°$. The straight line gives the excitation energy of the residual ^{29}Si nucleus.

described by the Rutherford formula, the ^{29}Si and ^{30}Si targets had a nuclear density of $(2.9 \pm 0.3)\times 10^{18}$ and $(3.6 \pm 0.4)\times 10^{18}$ nuclei/cm^2, respectively. The deuterons were detected by means of a ΔE-E counter telescope. The ΔE counter consisted of a transmission-mounted totally depleted surface-barrier detector of 100-μ thickness. The E counter was a 2000-μ-thick surface-barrier detector. The defining aperture, in front of the E counter, was circular and subtended a solid angle of 6.64×10^{-4} sr. Deuterons were discriminated from other $Z=1$ reaction products by a particle identifier similar to that designed by Goulding *et al.*[11] The effectiveness of this system can be assessed from the mass spectrum shown in Fig. 1. Two pulse-height spectra from the multichannel analyzer are shown in Figs. 2 and 3 for the ^{29}Si$(p,d)^{28}$Si and ^{30}Si$(p,d)^{29}$Si reactions, respectively. The figures illustrate the relative intensities of the deuteron groups. An evaluation of these spectra yields an over-all resolution of 250 keV full width at half maximum, under typical operating conditions. The deuteron particle spectra were measured up to 120° in steps of 5°.

III. RESULTS

The deuteron spectrum from the ^{29}Si$(p,d)^{28}$Si reaction (Fig. 2) shows strong transitions to states at 0, 1.79, and 9.32 MeV. The $J^\pi = 4^+$ state at 4.61 MeV is only weakly excited and in a direct pick-up mechanism should involve the transfer of a g-wave neutron. The $J^\pi = 0^+$ states are excited by removal of a $2s_{1/2}$ neutron, while the $J^\pi = 2^+, 3^+$ states are

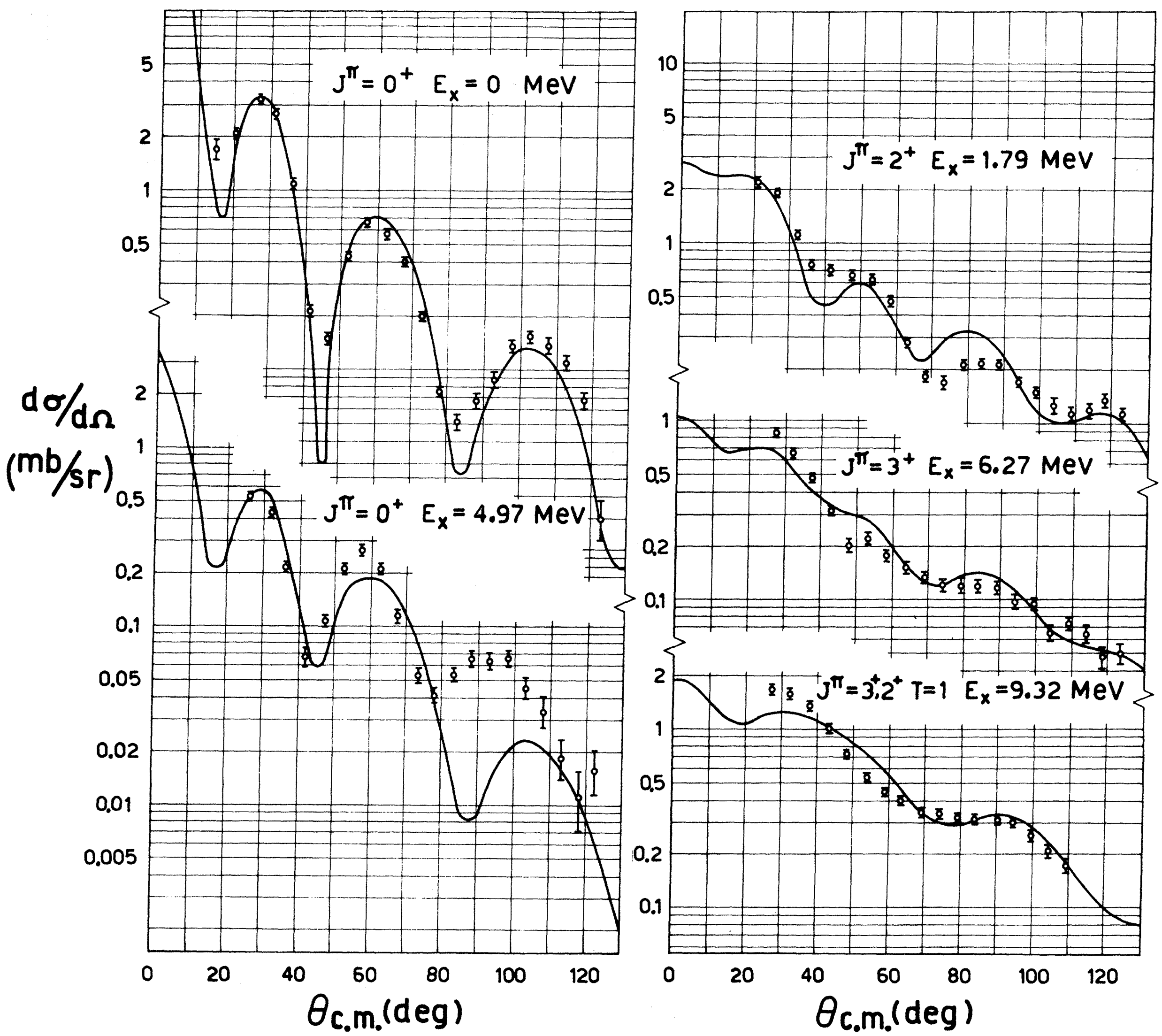

FIG. 4. Theoretical fits to the deuteron angular distributions for the ^{29}Si$(p,d)^{28}$Si reaction using the distorted-wave calculations described in the text. The errors shown are due only to statistical uncertainties.

excited by a $1d_{5/2}$ neutron pick up.[4] The latter states are described in a pure shell-model picture as 1p-1h states of a $[2s_{1/2}, (d_{5/2})^{-1}]$ configuration. These states have $J^\pi = 2^+, 3^+$ both with $T = 0$ and $T = 1$ isobaric spin. In this scheme, the strong transition observed at 9.32 MeV corresponds to the isobaric analog states of ^{28}Al ($J^\pi = 3^+$ and 2^+, $T = 1$ unresolved doublet). The remaining weakly excited state or group of states near 6.45-MeV excitation were not included in the analysis. The deuteron spectrum from the ^{30}Si$(p, d)^{29}$Si reaction (Fig. 3) shows strong transitions to states at 0, 2.03,

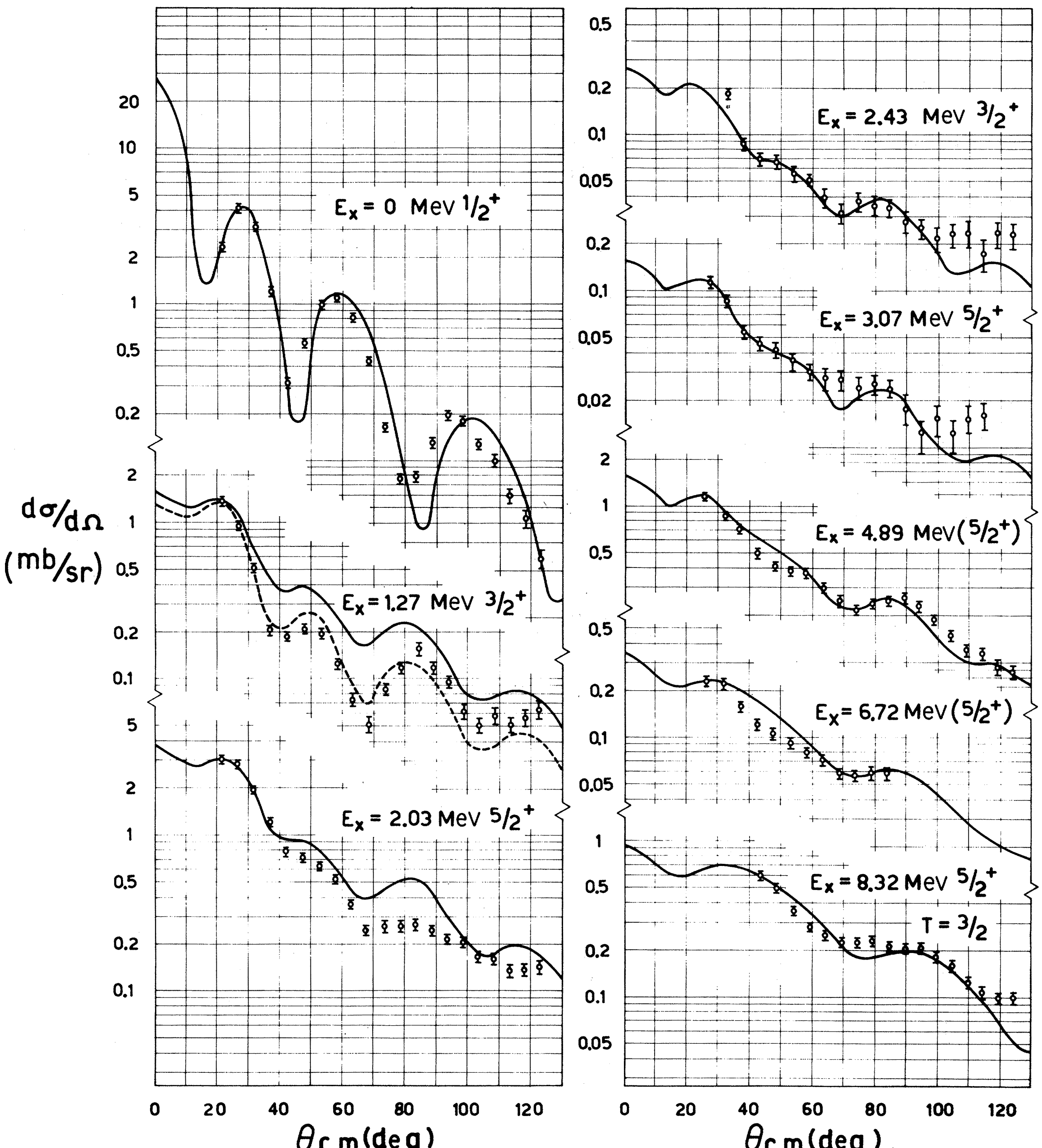

FIG. 5. Angular distributions and distorted-wave curves for the ^{30}Si$(p, d)^{29}$Si reaction. The dashed curve for the transition to the 1.27-MeV state has been obtained using a different binding energy for the transferred neutron (−9.35 MeV). The corresponding spectroscopic factor is 0.44.

TABLE I. Optical-model parameters. The optical potential was of the form
$V(r) = -V(e^x+1)^{-1} - i\left(W - 4W'\frac{d}{dx'}\right)(e^{x'}+1) + V_C(r,r_C)$ with $x=(r-r_0A^{1/3})/a$ and $x'=(r-r_0'A^{1/3})/a'$.

Channel	V (MeV)	W (MeV)	W' (MeV)	r_0 (fm)	a (fm)	r_0' (fm)	a' (fm)	r_C (fm)
^{29,30}Si + p	41.69	8.53	0	1.20	0.71	1.43	0.37	1.25
^{28,29}Si + d	80	0	27.40	1.10	0.78	1.51	0.48	1.30
^{28,29}Si + n	Ref. a			1.25	0.65			

[a] Adjusted to give the transferred neutron a binding energy of $Q(p,d) - 2.22$ MeV.

4.89, and 8.32 MeV. The latter is the isobaric analog to the ground state of ^{29}Al ($J^\pi = \frac{5}{2}^+$, $T=\frac{3}{2}$). The remaining states are excited to a smaller extent and are due to neutron pick up from the $1d_{5/2}$, $1d_{3/2}$, and $1f_{7/2}$ shells.

Deuteron angular distributions are shown in Figs. 4 and 5, respectively. Quantitative information on the strength S_{lj} of the various transitions was obtained in the usual fashion by comparing experimental and calculated differential cross sections, as related in the expression

$$\sigma(\theta)_{\exp} = 2.29 C^2 \sum S_{lj}\sigma_{lj}(\theta)_{\mathrm{D.W.}},$$

where C is the isospin Clebsch-Gordan coupling coefficient and S_{lj} is the spectroscopic factor. The distorted-wave curves, also shown in Figs. 4 and 5, were calculated in the local zero-range approximation with zero lower cut off with the code DWUCK,[12] using the optical-model parameters listed in Table I. The proton optical-model parameters used are those obtained by Jones, Johnson, and Griffiths[5] in the analysis of proton elastic scattering on ^{28}Si and of the ^{28}Si$(p,d)^{27}$Si reaction at 27.6 MeV. The use of sets of parameters for deuterons on silicon isotopes found in the literature, such as those of Hinterberger *et al.*[13] and Perey and Perey,[14] gives unsatisfactory fits to the shapes of the angular distributions. The parameters finally used in the present analysis were obtained from those reported in Ref. 5, with small adjustments made in order to achieve a satisfactory agreement with the angular distributions for the ground-state transitions. These latter, being $l=0$ curves, show a marked oscillatory behavior and are therefore sensitive to the optical-model parameters.

Absolute spectroscopic factors (listed in Table II) were extracted from the experimental data by normalizing the theoretical curves at the maximum

TABLE II. Absolute spectroscopic factors C^2S_{lj} for neutron pick up from ^{29}Si and ^{30}Si. The errors for the excitation energies have been evaluated not to be larger than ±80 keV.

E_x (MeV)	J^π	$C^2S\,(1d_{5/2})$	$C^2S\,(2s_{1/2})$	$C^2S\,(1d_{3/2})$	$C^2S\,(1f_{7/2})$
			^{28}Si		
0.0	0^+		0.45		
1.79	2^+	0.86			
4.97	0^+		0.12		
6.27	3^+	0.83			
9.32	$3^+, 2^+ (T=1)$	1.58			
Total strength		3.27	0.57		
			^{29}Si		
0.0	$1/2^+$		0.68[0.8] [a]		
1.27	$3/2^+$			0.70[0.7]	
2.03	$5/2^+$	1.77[1.7]			
2.43	$3/2^+$			0.13[0.17]	
3.07	$5/2^+$	0.08[0.10]			
3.62	$7/2^-$				0.17[0.08]
4.89	$(5/2)^+$	1.19[1.0]			
6.72	$(5/2)^+$	0.35[0.3]			
8.32	$5/2^+$ $(T=3/2)$	1.66[2.0]			
Total strength		5.05	0.68	0.83	0.17

[a] The spectroscopic factors in square brackets are those obtained from the ^{30}Si$(d,t)^{29}$Si reaction at 22.5 MeV studied by Dehnhard and Yntema (see Ref. 6).

of the observed experimental cross sections. The deuteron parameters, for which the disagreement between calculated and experimental angular distributions is relatively less marked (Set 2 of Ref. 13 and Set b of Ref. 14), give spectroscopic factors which are, respectively, about 20% higher and lower than those reported here.

The angular distributions of deuterons leading to the 4.61-MeV state of ^{28}Si and to the 3.62-MeV state of ^{29}Si are shown in Figs. 6 and 7, respectively. The curves reported in these figures are those obtained by the distorted-wave theory and Hauser-Feshbach calculations (H-F). The code[15] used for H-F calculations permitted the evaluation of compound-nucleus contributions to the differential cross sections through the use of level densities,[16] and of an appropriate optical potential for incoming and outgoing particles. In the case of deuterons and protons, these were the same as those used in the distorted-wave calculations described above. The optical-model parameters of Perey and Buck as compiled by Rosen[17] were used for the neutrons. The α and ^{3}He parameters were those obtained by Nurzynski, Bray, and Robson[18] in the analysis of the ^{27}Al(^{3}He, α)^{26}Al reaction at 10 MeV.

Comparison of the observed data with the H-F predictions indicates that compound-nucleus processes are not able to account for more than 10% of the measured cross sections.

IV. DISCUSSION

The observed direct pick-up transitions to the low-lying states of ^{28}Si and ^{29}Si indicate considerable $1d_{5/2}$, $2s_{1/2}$, and $1d_{3/2}$ admixtures in the ^{29,30}Si ground states. The amount of such admixtures can be estimated by calculating the neutron occupation probabilities $V_{lj}^2 = \sum C^2 S_{lj}/2j+1$, which are given in Table III. One sees that the silicon isotopes show appreciable core excitation, the neutron being essentially split among the $1d_{5/2}$, $2s_{1/2}$, $1d_{3/2}$ orbits with also 2% of $1f_{7/2}$ component in ^{30}Si. It is interesting to note that, within the experimental uncertainty, the same neutron occupation number for the $2s_{1/2}$ orbit is found for all the silicon isotopes.

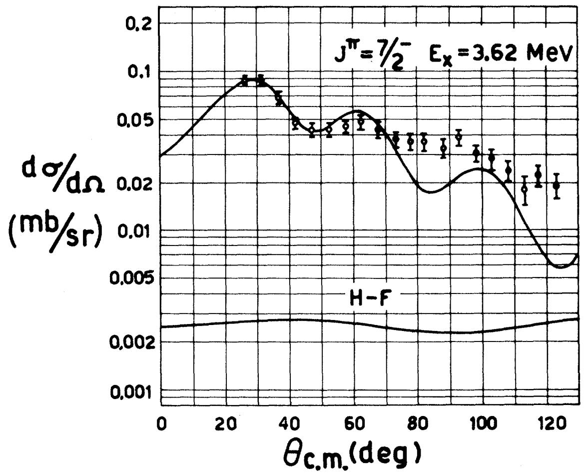

FIG. 7. Differential cross section for the excitation of the 3.62-MeV ($J^\pi = \frac{7}{2}^-$) state of ^{29}Si. The compound-nucleus contribution is given by the line labeled H-F. The other line is the distorted-wave prediction for $l_n = 3$.

In the $2s$-$1d$ shell one expects[19] strong $M1$ γ-ray transitions between the analog and antianalog states in those cases in which the unpaired nucleon involved in the transition has $j = l + \frac{1}{2}$. Recent results obtained by Meyer-Schützmeister *et al.*,[20] who studied the ^{27}Al(^{3}He,$p\gamma$)^{29}Si reaction, have shown that the γ decay from the analog state at 8.32 MeV ($J^\pi = \frac{5}{2}^+$, $T = \frac{3}{2}$) goes predominantly to the two ($J^\pi = \frac{5}{2}^+$, $T = \frac{1}{2}$) states at 2.03 and 4.89 MeV, with a branching ratio of 35 and 20%, respectively. The other two ($J^\pi = \frac{5}{2}^+$, $T = \frac{1}{2}$) states at 3.07 and 6.72 MeV are not fed measurably by γ decay from the analog state. The present results obtained for ^{29}Si, as summarized in Table II, are consistent with the above data. The two states predominantly fed by

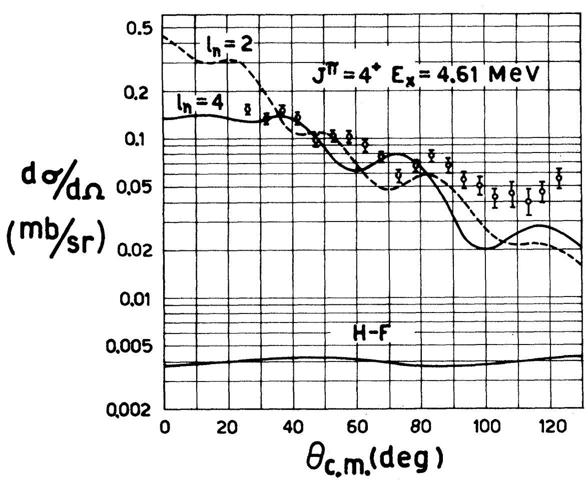

FIG. 6. Differential cross section for the excitation of the 4.61-MeV ($J^\pi = 4^+$) state of ^{28}Si. The compound-nucleus contribution as obtained from a Hauser-Feshbach calculation is given by the line labeled H-F. The other curves are the results of distorted-wave calculations for $l_n = 4$ (continuous line) and $l_n = 2$ (dashed line).

TABLE III. Neutron occupation numbers (%) for silicon isotopes.

Isotope	$1d_{5/2}$	$2s_{1/2}$	$1d_{3/2}$	$1f_{7/2}$
^{28}Si[a]	40	33	(30)	
^{29}Si	55	29		
^{30}Si	84	34	21	2

[a] For the ^{28}Si nucleus we have taken neutron occupation numbers derived from the experimental results of Ref. 5.

the γ decay show, in fact, a much larger $(d_{5/2})^{-1}$ strength than the other two.

Finally the excitation of the 4^+ state in ^{28}Si at 4.61 MeV should involve the transfer of a g-wave neutron. However, the corresponding spectroscopic factor $C^2S = 0.37$ gives a g admixture in the ground state of ^{29}Si considerably larger than that expected on the basis of a simple shell model. It is therefore more appropriate to assume that this level is not primarily excited by simple nucleon transfer but through target-excitation effects. Experimental and theoretical evidence[9, 10] has been reported on a two-step pick-up process. In this process the entrance or the exit channel is strongly coupled to a low-lying state corresponding to the excitation of a collective mode of the target or residual nucleus, respectively. This two-step pick-up process applied to the $^{29}Si(p, d)^{28}Si$ reaction allows excitation of the 4^+ state by a $d_{5/2}$ neutron transfer.

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