Transfer reactions for $^{28}Si+^{28}Si$ at $E_{lab}=151.25$ MeV

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Cross sections of one- and few-nucleon transfers in the reaction $^{28}Si+^{28}Si$ at $E_{lab}=151.25$ MeV have been measured with a quadrupole-dipole-dipole-dipole magnetic spectrometer. The one-neutron and one-proton transfers to corresponding shell model states in the pairs of mirror nuclei ^{29}Si-^{29}P and ^{27}Si-^{27}Al are found to be approximately equal. The cross sections for few-nucleon transfers to states with excitation energies $E_x<5$ MeV exhibit a strong enhancement of 1n1p over 2n and 2p and of 2n2p (i.e., 1α) over 2n1p or 1n2p transfers. A distorted-wave Born approximation analysis of the 1n and 1p transfers was performed. The derived spectroscopic factors display a high degree of symmetry with respect to isospin and are consistent with the widely varying values obtained in light ion studies.

I. INTRODUCTION

There are several reasons why the $^{28}Si+^{28}Si$ system is of particular interest for the study of heavy-ion transfer reactions. The ^{28}Si nucleus has a large permanent deformation, and a strong collective coupling between the ground and low excited states has been derived from a coupled-channels analysis of inelastic scattering.[1] Even though no evidence for deformation effects was found in studies of the one-proton transfer in the reactions $^{28}Si+^{48}Ca$ (Ref. 2) and $^{28}Si+^{40}Ca$ (Ref. 3), the fact that both projectile and target are deformed may lead to a somewhat more complex situation for $^{28}Si+^{28}Si$. A second particularity of this system are the wide and narrow resonances in the elastic and inelastic scattering channels, which are seen at large angles and over the wide range of bombarding energies from 80 to 125 MeV, which is high above the Coulomb barrier.[4] At present there is no heavier system known that exhibits the same phenomenon. It is generally thought that, as a necessary condition for the occurrence of such resonances, a lack of absorption of the surface partial waves is needed. Since in most models the absorptive potential caused by transfer reactions has a larger range than that from inelastic scattering, the resonance phenomenon would be expected to be related to the transfer cross sections (see, e.g., Ref. 5). More generally, a complete knowledge of the transfer channels is a prerequisite in any attempt to construct the absorptive potential microscopically.[6]

Apart from these special properties of the $^{28}Si+^{28}Si$ system, there are two basic questions concerning heavy-ion transfer reactions that still demand satisfactory answers: (i) Is our present knowledge of the reaction dynamics sufficient to reach a quantitative level in the description of these reactions, and (ii) are they useful tools to obtain nuclear structure information. Recent high resolution studies for ^{28}Si induced reactions on $^{40,48}Ca$ and ^{208}Pb targets have shown that the spectroscopic factors obtained in distorted-wave—Born-approximation (DWBA) analyses agree with those from light-ion work within the accuracy of the experimental and analysis procedures.[2,3,7] We have added to this line of investigation by measuring transfer cross sections for the $^{28}Si+^{28}Si$ reaction with sufficient energy resolution such that transfers to several discrete states in the final nuclei could be studied individually. An additional unique feature of this transfer study is that the symmetry of the system and the relative unimportance of the differences of the Coulomb trajectories in the various reaction channels at the chosen bombarding energy of more than twice the Coulomb barrier permit the comparison of transfers to corresponding states in mirror nuclei under virtually identical dynamical conditions.

II. EXPERIMENT

An isotopically enriched (99.9%) ^{28}Si target of 50 $\mu g/cm^2$ areal density on a carbon backing was bombarded with ^{28}Si beams of $E_{lab}=151.25$ MeV from the Brookhaven Tandem Van de Graaff facility. Reaction products were momentum analyzed by the quadrupole-dipole-dipole-dipole (QDDD) magnetic spectrometer and identified in a heavy-ion focal plane detector.[8] With this detector, which comprises a single ionization chamber with three energy loss anodes and a multiwire proportional counter with delay line readout for position determination, the various ion species were fully separated, except for a barely observable leakage of the order at 10^{-4} of the dominant elastic peak into the ^{27}Si channel. Examples of position spectra of ^{27}Si (13^+) and ^{27}Al (13^+) ions are shown in Fig. 1. The width of the observed single transfer peaks corresponds to $\Delta E \simeq 280$ keV [full width at half maximum (FWHM)].

The solid angle acceptance of the spectrometer was chosen as 20 mrad (horizontal, in the reaction plane) $\times$ 40 mrad (vertical). Data were taken at five reaction angles, $\theta_{lab}=10°$, 11°, 12°, 13.5°, and 15°. For reference, the quarter-point angle derived from the elastic scattering data is $\theta_{lab}^{1/4}=15°$ (Ref. 1). At each angle, two different settings of the spectrometer magnetic field were needed to span the desired range of ion momenta.

The yields of elastic scattering observed in two monitor detectors at forward angles were used for the relative normalization of different runs. The absolute normalization of the measured differential cross sections was achieved by requiring that the previously measured elastic scattering data[1] were reproduced.

Charge state distributions for ^{28}Si ions from elastic and inelastic (2^+) scattering were measured and found in good agreement with the phenomenological parametrization of Gould.[9] The analysis was therefore based on this parametrization with the widths of the assumed Gaussian charge state distribution reduced by 0.04 charge units, as suggested by the measured distributions. The adopted mean values and widths, in our region of ions species and energies, are on average larger by 0.38 and 0.24 charge units, respectively, than those of the prescription given by Betz.[10] We note that uncertainties in the charge state intensities have a negligible influence on the neutron transfer data since only Si ions in the dominant 13^+ state were included both in the analysis and in the absolute normalization. The proton transfer data are derived from the yields of the less abundant Al (13^+) and P (13^+) ions. We estimate, however, that the errors of the cross section due to the uncertainty of the charge state distribution do not exceed 5%. The consistency of the data is confirmed by the agreement of the transfer cross sections extracted from the spectra of each of the two reaction products.

The uncertainty of the quoted absolute cross sections for isolated transfers is estimated to be about ±10%, which arises from uncertainties in the peak integration and in the overall normalization with respect to elastic scattering.

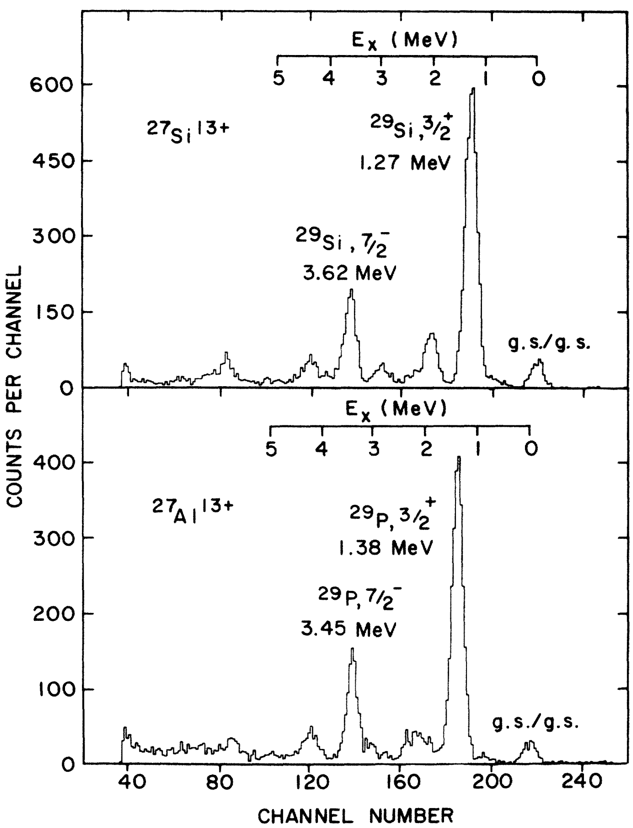

FIG. 1. Position spectra of ^{27}Si (13^+) and ^{27}Al (13^+) ions following one neutron and one proton transfer, respectively, from a measurement at $\theta_{lab}=12°$. The transfers to resolved states in ^{29}Si (and ^{27}Si ground state) and ^{29}P (and ^{27}Al ground state) are labeled and the scale of excitation energies is given. Note the similarity of the spectra shapes. The cross sections are also very similar (Tables III and V) in both cases; the higher count rate of ^{27}Si ions reflects the larger probability of the 13^+ charge state for Si as compared to ^{27}Al ions at these energies. The elastic ^{28}Si peak had its centroid in channel 84 in this run and caused the minor structures seen at this position.

III. RESULTS

Table I gives a list of energy integrated cross sections, $0 \le E_x \le 5$ MeV, for identified transfers measured at $\theta_{lab}=12°$, which is near or slightly behind the angle of maximum cross section for most of the transfer channels. The one-nucleon transfers leading to the pairs of mirror nuclei ^{29}Si/^{29}P and ^{27}Si/^{27}Al, respectively, constitute, by far, the strongest channels. The 1n1p and 2n2p (equivalent to 1α) transfers are weaker by 1 order of magnitude, but considerably stronger than the 2n, 2p, 2n1p, or 1n2p transfers. There is a general tendency, however, for increasing multinucleon transfer strengths with increasing excitation energy, as expected from semiclassical considerations.[11]

Transfers to discrete final states were resolved and identified in the 1n, 1p, and 1α channels. In the 1n and 1p channels, the transfers to the $\frac{1}{2}^+$ ground and to the $\frac{3}{2}^+$ and $\frac{7}{2}^-$ excited states in ^{29}Si and ^{29}P (with ^{27}Si and ^{27}Al in their ground states) form isolated peaks in the position spectra (Fig. 1). In addition, four groups of unresolved transfers with centroids near $\langle E_x \rangle = 0.8$, 2.1, 3.0,

TABLE I. Cross sections, measured at $\theta_{lab}=12°$ and integrated over $0 \le E_x \le 5$ MeV, for identified transfers in the reaction ^{28}Si+^{28}Si at $E_{lab}=151.25$ MeV (Det. denotes detected, Trans. transferred).

Det.	Trans.	Q_{gg} (MeV)	$(d\sigma/d\Omega)_{c.m.}$ (mb/sr)	$\theta_{c.m.}$[a] (deg)
^{27}Si	1n	−8.70	7.66	24.6
^{29}Si	1n	−8.70	6.62	25.5
^{30}Si	2n	−11.40	0.04	26.3
^{27}Al	1p	−8.84	7.79	24.6
^{29}P[b]	1p	−8.84	5.30	25.6
^{26}Mg	2p	−12.70	0.06	24.5
^{30}S	2p	−12.70	0.02	26.5
^{26}Al	1n1p	−10.57	0.58	24.3
^{30}P	1n1p	−10.57	0.46	26.2
^{25}Al	2n1p	−9.63	0.08	23.8
^{31}S	1n2p	−10.79	0.07	26.8
^{24}Mg	1α	−3.04	0.24	22.8

[a]Calculated for $E_x=2.5$ MeV.
[b]Particle unstable at $E_x > 2.75$ MeV.

and 4.3 MeV were observed. They cover regions of (total) excitation energy where the possibilities of excitations of the donor or acceptor nucleus and of mutual excitation cause a clustering of transfer channels. In the relevant range of particle momenta, the position spectra are free of contributions from reactions on the carbon backing and on possible oxygen contaminants as a result of the kinematics and of the unfavorable Q values of these transfer reactions.

The cross section angular distributions for the isolated transfer peaks are shown in Fig. 2, and, for the unresolved transfers, in Fig. 3. In the latter case only the data derived from the detection of ^{27}Si and ^{27}Al are displayed. In the ^{29}Si and ^{29}P spectra some of these groups are less well defined since the dominating peaks are broadened by the recoil momenta of the decay γ rays. In the ^{29}P spectra the transfers to higher lying states are not seen at all since this nucleus is unstable against proton decay at $E_x>2.75$ MeV. Figure 2 also contains the results of the DWBA calculations, which will be discussed in the following section.

The measured angular distributions peak at angles $20^\circ \leq \theta_{c.m.} \leq 24^\circ$, which is about 5°–10° forward of the quarter point angle $\theta^{1/4}_{c.m.}=30^\circ$ (Ref. 1) and, on the average, 2° forward of the peak positions given by the DWBA calculations (Fig. 2). Only in the case of the transfers with $\langle E_x \rangle \simeq 4.3$ MeV are the maxima of the cross sections at $\theta_{c.m.} \leq 20^\circ$ outside the angular range covered by the experiment.

The dominant feature of the one nucleon transfers is the striking similarity, already obvious in the spectra (Fig. 1), of the cross sections for transfers to corresponding shell model states in the neutron and proton channels. The differences in the binding energies and the different charge distributions in the exit channels have apparently very small effects.

In the spectra of ^{24}Mg (12^+) ions several discrete lines are seen, together with a continuum rising with increasing excitation energy (Fig. 4). Two of these lines were identified as stemming from one-alpha transfers to excited states in ^{32}S at $E_x=5.01$ MeV (3^-) and $E_x=6.76$ MeV. The angular distributions of these transfers are shown in Fig. 5, including the data from the detection of ^{32}S ions.

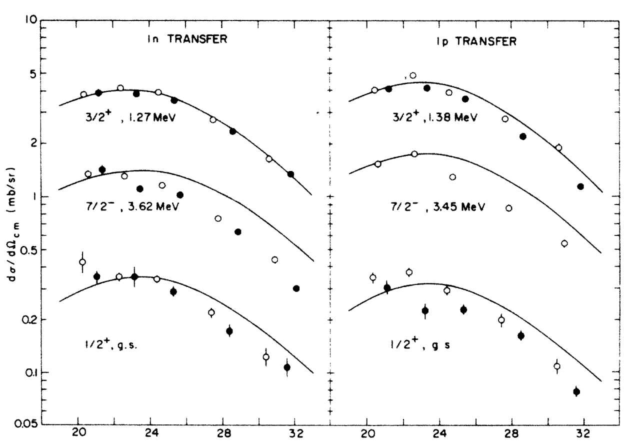

FIG. 2. Angular distributions for the one neutron and one proton transfers to the indicated states in ^{29}Si and ^{29}P (with ^{27}Si and ^{27}Al ground states, respectively). Except for the proton unstable $\frac{7}{2}^-$, $E_x=3.45$ MeV state in ^{29}P all transfers were identified and analyzed in the spectra of the donor (open circles) and acceptor (solid circles) nuclei. The lines represent results of DWBA calculations described in the text.

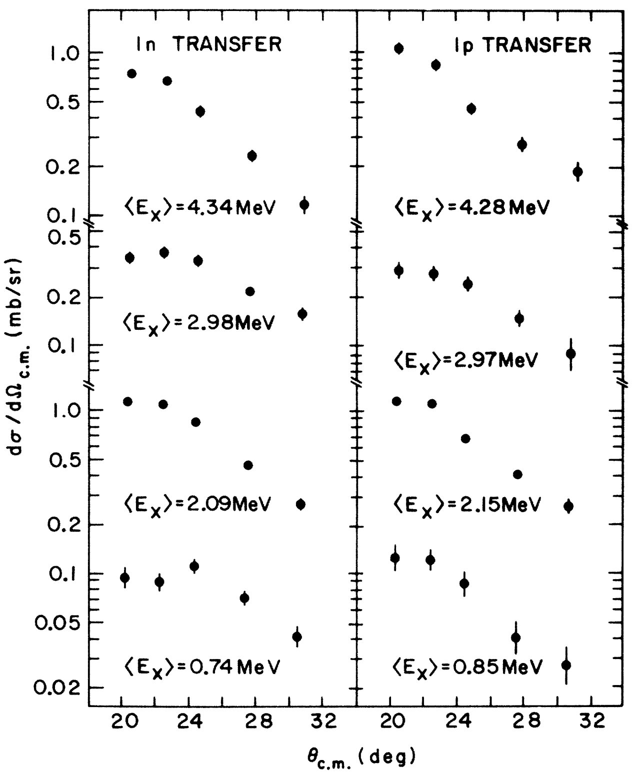

FIG. 3. Angular distributions for the four unresolved groups of 1n and 1p transfers. The measured centroids are used as labels. Only the data from the analysis of the spectra of ^{27}Si and ^{27}Al donor nuclei are given since the increased widths of the major lines in the ^{29}Si and ^{29}P spectra, due to γ recoil, lead to a poorer definition of the groups.

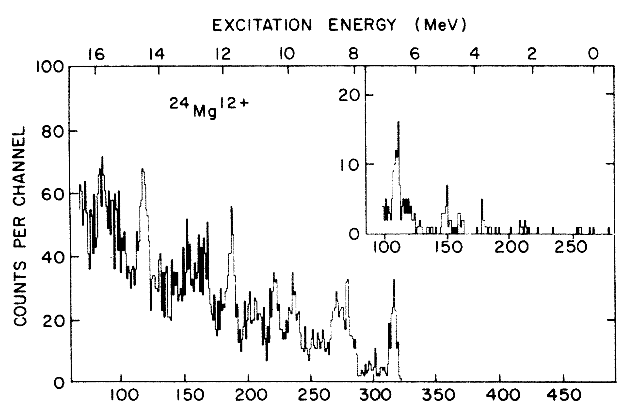

FIG. 4 Position spectra of ^{24}Mg ions produced in four nucleon transfers from a measurement at $\theta_{lab}=12^\circ$. The focal plane detector ends at channel 325; the low excitation part of the spectrum (inset) was measured in a run with higher magnetic field. The excitation energies of the ^{24}Mg-^{32}S system corresponding to the measured momenta of ^{24}Mg are given in the top scale.

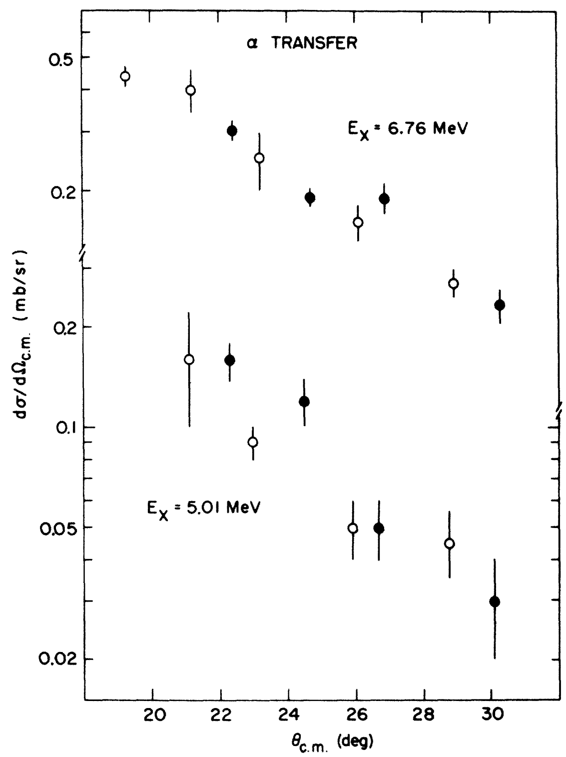

FIG. 5. Angular distributions of two isolated groups associated with transfers to the $E_x = 5.01$ and 6.76 MeV states in ^{32}S (^{24}Mg ground state). The open and solid symbols indicate cross sections extracted from ^{24}Mg (12^+) and ^{32}S (14^+) spectra, respectively.

Their slopes are comparable to those of the one nucleon transfers, but the angles of maximum cross section are forward of $\theta_{c.m.} = 20°$. These states were previously observed in the ^{28}Si(^{18}O,^{14}C) and ^{28}Si(^{6}Li,d) transfer reactions.[12,13]

Lower lying states are only weakly populated, particularly the ground state, and the 2^+ (2.23 MeV) and 4^+ (4.46 MeV) excited states are barely seen in our spectra (Fig. 4). For the discrete peaks at higher excitation energies, we obtain $E_x = 8.3$, 9.8, 10.4, 11.7, and 14.4 MeV from our energy calibration. Peaks at these energies also appear in the (^{6}Li,d) data of Tanabe et al.;[13] some of them may represent states with spins $I > 4\hbar$ in ^{32}S, which, according to shell model calculations, are expected at $E_x > 8$ MeV (Ref. 14). A series of states with spin $I \geq 4\hbar$ at $11 \leq E_x \leq 16$ MeV was reported recently and a quasimolecular structure was suggested.[15] It is not obvious, however, whether some of these states might be associated with those seen by Tanabe et al.[13] and in this work.

IV. ANALYSIS

The analysis was restricted to the one neutron and one proton channel since an adequate multistep description of the few nucleon and alpha transfers was considered to be beyond the scope of this work. The single nucleon transfer data were analyzed in the framework of the DWBA theory, and a symmetrized version of the full recoil finite range program ONEFF/DIWRI (Ref. 16) was used for the calculations. It is worth mentioning that for the present angular range the effect of the symmetrization is negligible.

TABLE II. Optical model parameters.

	Potential	Depth (MeV)	Radius parameter (fm)	Diffuseness (fm)	$\chi^{2\,a}$
A	Real	37.10	1.205	0.624	9.36
	Imaginary	24.10	1.136	0.655	
B	Real	37.10	1.162	0.700	4.17
	Imaginary	30.00	1.150	0.550	

[a]χ^2 per point obtained in an optical model fit of elastic scattering data in the range $8° \leq \theta_{c.m.} \leq 59°$; see Ref. 1.

The optical potential was of the form

$$U(r) = -V(r) - iW(r) ,$$

$$V(r) = V_0(1+\exp\{[r - r_0(A_1^{1/3} + A_2^{1/3})]/a\})^{-1} ,$$

$$W(r) = W_0(1+\exp\{[r - r_0'(A_1^{1/3} + A_2^{1/3})]/a'\})^{-1} ,$$

where V_0, W_0 denote the real and imaginary potential depths, r_0 and r_0' the radius parameters, a and a' the diffusenesses, and A_1 and A_2 the mass numbers. The parameters derived from fits to the ^{28}Si+^{28}Si elastic scattering data[1] in the angular range $8° \leq \theta_{c.m.} \leq 59°$ are listed in Table II. Two slightly different potentials were found to yield nearly equally good fits. The potential denoted B gives a somewhat smaller χ^2 (Table II) and was adopted for both entrance and exit channels in the DWBA calculations. The calculated transfer cross sections decrease by about 25% if potential A is used instead. The bound-state potentials also had Woods-Saxon shapes with radius parameter $r_0 = 1.2$ fm, diffuseness $a = 0.65$ fm, and a depth adjusted to give the experimental binding energy of the transferred nucleon. A Thomas-type spin orbit interaction of strength $\lambda = 25$ was included in the bound state potential. If the radius parameter is increased to $r_0 = 1.25$ fm, a value sometimes used in the analysis of light-ion reactions, the calculated transfer cross sections increase by a factor of about 1.4. This factor, as well as the dependence on the optical potential, is nearly the same for all transfers and therefore of no concern for relative comparisons. It demonstrates, however, the uncertainty in the absolute cross section from DWBA analysis.

A. Resolved peaks

In Fig. 2 the calculated single nucleon transfer angular distributions are compared to the data. Their strengths were adjusted to reproduce the maxima of the measured cross sections. For the transfers to the $\frac{3}{2}^+$ states, the strongest individual transfers, a very good description of the measured angular distributions is achieved. In the remaining cases the maxima and their angular positions are not as well defined. We interpret the values measured near $\theta_{c.m.} = 22°$ as maxima, which leads to a displacement by about 2° of the measured and calculated distributions

TABLE III. Spectroscopic factors for resolved transfers.

Transfer channel			L_{tr}	$d\sigma/d\Omega$ [a] (mb/sr) Expt.	DWBA [b]	S^+S^- [c] This work	Light ions [d]	$S^+S^-(\text{heavy})/S^+S^-(\text{light})$ [e]
1n	$^{29}Si(\frac{1}{2}^+,\text{g.s.})$	$^{27}Si(\frac{5}{2}^+,\text{g.s.})$	2	0.35	0.37	0.95	2.31	0.41
	$^{29}Si(\frac{3}{2}^+,1.27)$	$^{27}Si(\frac{5}{2}^+,\text{g.s.})$	1,2,3,4	4.0	1.80	2.23	2.97	0.75
	$^{29}Si(\frac{7}{2}^-,3.62)$	$^{27}Si(\frac{5}{2}^+,\text{g.s.})$	1,2,3,4,5	1.4	1.38	1.02	1.83	0.56
1p	$^{29}P(\frac{1}{2}^+,\text{g.s.})$	$^{27}Al(\frac{5}{2}^+,\text{g.s.})$	2	0.32	0.29	1.11	2.07	0.54
	$^{29}P(\frac{3}{2}^+,1.38)$	$^{27}Al(\frac{5}{2}^+,\text{g.s.})$	1,2,3,4	4.4	1.75	2.51	2.68	0.94
	$^{29}P(\frac{7}{2}^-3.45)$	$^{27}Al(\frac{5}{2}^+,\text{g.s.})$	1,2,3,4,5	1.75	2.02 [f]	0.87	1.53	0.57

[a]Values at maxima of angular distributions (see text).
[b]With potential B (Table II) and $r_0=1.2$ fm for the bound state potential.
[c]$S^+S^-=(d\sigma/d\Omega_{\text{expt}})/(d\sigma/d\Omega_{\text{DWBA}})$.
[d]From Table IV.
[e]Ratio of values given in preceding columns.
[f]The proton is unbound in ^{29}P, but a binding energy of -0.1 MeV was used in the calculations.

at the larger angles (Fig. 2). Had we chosen to reproduce the falling slope region, an adjustment in intensity of about 20% would have been required, resulting in a corresponding decrease of the spectroscopic factors.

The spectroscopic information extracted from the comparison of the measured and calculated cross section maxima is summarized for the individually resolved transfers in Table III. Since the DWBA cross sections are nearly the same for both neutron and proton transfers to corresponding shell model states, the observed symmetry in the experimental data is preserved in the derived spectroscopic factors. The differences are largest for the transfers to the $\frac{7}{2}^-$ states, possibly so because here the binding energy of the neutron in ^{28}Si is -4.85 MeV, whereas the proton in ^{29}P is unbound.

As a source of spectroscopic factors from light-ion work, we have first chosen the compilation of Endt and Van der Leun.[17] These spectroscopic factors are averages over results of several investigations and are considered to form a consistent set. The values relevant for this work are listed in Table IV.

For the three resolved transfers in both the 1n and 1p channel that lead to states with large single-particle plus ^{28}Si (g.s.) core amplitudes in their wave functions, the heavy-ion spectroscopic factors are between 40% and 100% of those given by Endt and Van der Leun. This is

TABLE IV. Shell model states and spectroscopic factors from light ion work, as compiled in Ref. 17.

State	Nuclide	E_x (MeV)	S [a]	Nuclide	E_x (MeV)	S [a]
$1d_{5/2}$	^{27}Si	0.0	3.45	^{27}Al	0.0	3.05
$2s_{1/2}$		0.78	0.65		0.84	0.60
$1d_{3/2}$		0.96	0.60		1.01	0.50
$1d_{5/2}$		2.65	0.50		2.73	0.47
$1d_{3/2}$		2.86 [b]	0.55		2.98	0.35
$2s_{1/2}$		3.54	0.02		3.68	0.04
$1p_{1/2}$		4.14	1.60		4.05	1.45
$1d_{5/2}$		4.29	0.25		4.41	0.38
$2s_{1/2}$	^{29}Si	0.0	0.67	^{29}P	0.0	0.68
$1d_{3/2}$		1.27	0.86 [c]		1.38	0.88
$1d_{5/2}$		2.03	0.24		1.95	0.11
$1d_{3/2}$		2.43	0.05		2.42	0.03
$1d_{5/2}$		3.07	0.09		3.11	0.06
$1f_{7/2}$		3.62	0.53		3.45	0.50
$2p_{3/2}$		4.93	0.57		4.34	0.36

[a]Spectroscopic factors in a nonisospin notation, i.e., equal to C^2S in an isospin notation.
[b]$I=\frac{5}{2}$ is not excluded for this state; see Refs. 17 and 18.
[c]As required by $\Sigma S(1d_{3/2})\leq 1.0$; see Ref. 17.

TABLE V. Results of DWBA calculations for unresolved groups.

ΣE_x (MeV)	Transfer channel Nuclide	E_x (MeV)	J^π	Nuclide	E_x (MeV)	J^π	Light ion[a] S^+S^-	DWBA $d\sigma/d\Omega$[b] (mb/sr)	Calc. $d\sigma/d\Omega$[b] (mb/sr)	Calc. $\langle E_x \rangle$ (MeV)	Expt. $d\sigma/d\Omega$[b] (mb/sr)	Expt. $\langle E_x \rangle$ (MeV)	$\frac{d\sigma/d\Omega(\text{expt})}{d\sigma/d\Omega(\text{calc})}$
0.78	^{27}Si	0.78	$\frac{1}{2}^+$	^{29}Si	0.0	$\frac{1}{2}^+$	0.44	0.52	0.28	0.82	0.12	0.74	0.43
0.96		0.96	$\frac{3}{2}^+$		0.0	$\frac{1}{2}^+$	0.40	0.14					
2.03		0.0	$\frac{5}{2}^+$		2.03	$\frac{5}{2}^+$	0.83	1.00	1.74	2.09	1.10	2.09	0.63
2.05		0.78	$\frac{1}{2}^+$		1.27	$\frac{3}{2}^+$	0.56	1.22					
2.23		0.96	$\frac{3}{2}^+$		1.27	$\frac{3}{2}^+$	0.52	0.05					
2.43		0.0	$\frac{5}{2}^+$		2.43	$\frac{3}{2}^+$	0.17	1.20					
2.65		2.65	$\frac{5}{2}^+$		0.0	$\frac{1}{2}^+$	0.34	0.06	0.63	2.93	0.38	2.98	0.60
2.81		0.78	$\frac{1}{2}^+$		2.03	$\frac{5}{2}^+$	0.16	1.49					
2.86		2.86	$\frac{3}{2}^+$		0.0	$\frac{1}{2}^+$	0.37	0.04					
2.99		0.96	$\frac{3}{2}^+$		2.03	$\frac{5}{2}^+$	0.14	1.14					
3.07		0.0	$\frac{5}{2}^+$		3.07	$\frac{5}{2}^+$	0.31	0.63					
0.84	^{27}Al	0.84	$\frac{1}{2}^+$	^{29}P	0.0	$\frac{1}{2}^+$	0.41	0.39	0.20	0.87	0.13	0.85	0.65
1.01		1.01	$\frac{3}{2}^+$		0.0	$\frac{1}{2}^+$	0.34	0.11					
1.95		0.0	$\frac{5}{2}^+$		1.95	$\frac{5}{2}^+$	0.34	1.02	1.05	2.15	1.12	2.15	1.07
2.22		0.84	$\frac{1}{2}^+$		1.38	$\frac{3}{2}^+$	0.53	1.09					
2.39		1.01	$\frac{3}{2}^+$		1.38	$\frac{3}{2}^+$	0.44	0.04					
2.42		0.0	$\frac{5}{2}^+$		2.42	$\frac{3}{2}^+$	0.09	1.22					
2.73		2.73	$\frac{5}{2}^+$		0.0	$\frac{1}{2}^+$	0.32	0.05	0.33	2.96	0.28	2.97	0.85
2.79		0.84	$\frac{1}{2}^+$		1.95	$\frac{5}{2}^+$	0.07	1.50					
2.96		1.01	$\frac{3}{2}^+$		1.95	$\frac{5}{2}^+$	0.06	1.14					
2.98		2.98	$\frac{3}{2}^+$		0.0	$\frac{1}{2}^+$	0.24	0.03					
3.11		0.0	$\frac{5}{2}^+$		3.11	$\frac{5}{2}^+$	0.18	0.76[c]					

[a]See Table IV.

[b]Values at maxima of angular distributions (see text).

[c]Proton is unbound, value calculated with binding energy of -0.1 MeV.

somewhat outside the range of uncertainty of the analysis procedure as defined above, in particular, since the use of $r_0=1.25$ fm in the bound-state potential would even widen the gap. It is to be emphasized, however, that a quantitative comparison is also severely limited by the considerable uncertainties in the spectroscopic factors from light-ion reactions, as will be demonstrated in the following.

Recent investigations of the $^{28}Si(p,d)^{27}Si$ (Ref. 19) and $^{28}Si(d,p)^{29}Si$ (Ref. 20) reactions have resulted in values of $S^-=2.88$ for ^{27}Si (g.s., $1d_{5/2}$) and $S^+=0.32$, 0.69, and 0.45 for the $2s_{1/2}$, $1d_{3/2}$, and $1f_{7/2}$ states in ^{29}Si, $E_x=0.0$, 1.27, and 3.62 MeV, respectively. With these values the light-ion S^+S^- products given in Table III reduce to 0.92, 1.99, and 1.30, in excellent agreement with the heavy-ion result. More recent studies[21,22] of the $^{28}Si(^3He,d)^{29}P$ reaction at various energies have also resulted in spectroscopic factors that are smaller than those compiled by Endt and Van der Leun.[17] Matsuoka *et al.*[21] report $S^+=0.55$ and 0.51 for the $2s_{1/2}$ (g.s.) and $1d_{3/2}$ ($E_x=1.38$ MeV) states in ^{29}P, respectively; the results of Djaloeis *et al.*[22] are $S^+=0.45$ and 0.23. With these values the light-ion S^+S^- reduce to 1.68 or 1.37 for the g.s. transfer and to 1.56 or 0.71 for the $1d_{3/2}$ ($E_x=1.38$ MeV) transfer, which improves the agreement with the heavy ion values, but not to the same extent as in the 1n transfer case. In particular, the symmetry with respect to isospin, which is a clear result of the experiment (Figs. 1 and 2) and of the DWBA calculations (Table III) and which is preserved in the compilation of Ref. 17, is not reflected in these recently reported spectroscopic factors. The discussion has shown, however, that the deviations of the heavy-ion spectroscopic factors from those given by Endt and van der Leun[17] should not necessarily be interpreted as a shortcoming of the DWBA in the heavy-ion case.

As a conclusion from the analysis of the resolved transfers, we find that the DWBA model for direct transfer reactions gives as good a description for the one nucleon transfer between heavy ions as it does for light ion induced reactions. Two-step and higher order processes may be important to some extent and were found to be so in, e.g., the $^{28}Si(d,p)$ reaction,[20] but the DWBA provides an excellent first order description of the transfer process. This is in line with conclusions drawn from other high-resolution studies of heavy-ion transfer reactions.[2,3,7,23,24]

B. Unresolved groups

Motivated by the good predictions obtained for the singly resolved transfers, we used the DWBA to calculate cross sections for the series of transfers that form the unresolved groups at $\langle E_x \rangle \simeq 0.8$, 2.1, and 3.0 MeV. Because of the large number of possibly contributing transfers, the calculations were not extended to the groups at $\langle E_x \rangle \simeq 4.3$ MeV. It was tested, however, whether other transfers might add to the $\frac{7}{2}^-$ peaks at $E_x=3.62$ and 3.45 MeV in the 1n and 1p channels, respectively. According to the DWBA calculations, their strengths are negligible.

All the calculated angular distributions had the same shape as those displayed in Fig. 2, with maxima around $\theta_{c.m.}=23°$ and, as before, the cross sections measured in the range $20° \leq \theta_{c.m.} \leq 22°$ were taken as the experimental maxima. These maximum cross sections are listed in Table V. The calculated cross sections for the groups were obtained by multiplying the DWBA cross sections with the light-ion S^+S^- factors and by summing over the channels contributing to each group. Again, the set of light-ion spectroscopic factors from Ref. 17 and given in Table IV was used in order to permit an internally consistent comparison with the results for the resolved transfers listed in Table III. We find that, in fact, the ratios of experimental to calculated cross sections are in the same range, 0.4—1.0, as for the resolved transfers (last columns of Tables III and V). The excitation energy centroids of the groups are also satisfactorily reproduced. We note again that both the measured cross sections and the DWBA cross sections (column 9 of Table V) display a remarkable degree of symmetry with respect to isospin. This strongly suggests the same for the wave functions of the pairs of mirror nuclei $^{27}Si/^{27}Al$ and $^{29}Si/^{29}P$. As an example, the spectroscopic factors of the $1d_{5/2}$ states at $E_x=2.03$ and 1.95 MeV in ^{29}Si and ^{23}P are listed as 0.24 and 0.11 in Table IV. An analysis of the individual contributions to the calculated cross sections for the groups at $\langle E_x \rangle \simeq 2.1$ MeV shows that this difference is the main reason for the asymmetry of the predictions. The symmetry of the heavy-ion data therefore indicates that these two spectroscopic factors should be about the same.

V. CONCLUSION

The high resolution study of quasielastic transfers in the $^{28}Si+^{28}Si$ reaction at 151.25 MeV has shown that the mechanism of one nucleon transfer is well approximated by a one-step description, even though both reaction partners are deformed, and that cross sections can be reliably predicted by the DWBA model. The accuracy is found to be of the order of a factor of $\simeq 1.5$ and at least partly associated with uncertainties of spectroscopic factors derived from analyses of light ion induced transfer reactions.

A particular advantage of the heavy-ion reactions studied here lies in the fact that transfers to corresponding states in mirror nuclei can be studied under nearly identical dynamical conditions. The data were found to exhibit a remarkable degree of symmetry with respect to isospin, thus reflecting the corresponding symmetry in the wave functions of the populated states.

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