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l = 1 transfer reaction ^{28}Si(^{10}B,^{9}Be)^{29}P$_{g.s.}$ (1/2$^+$)

W. Treu,* C. W. Towsley, K. G. Nair, and H. Voit*

Cyclotron Institute, Texas A&M University, College Station, Texas 77843

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The l = 1 single-nucleon transfer reaction ^{28}Si(^{10}B,^{9}Be)^{29}P$_{g.s.}$(1/2$^+$) has been investigated at incident energies of 59, 75, and 132 MeV. In addition, the transfer to the first (3/2$^+$) and second (5/2$^+$) excited states was observed. The data were analyzed using exact finite range distorted wave Born approximation calculations. The agreement between experimental data and calculations is rather good for all transitions.

[NUCLEAR REACTIONS ^{28}Si(^{10}B,^{9}Be), E=59, 75, 132 MeV (lab); measured $\sigma(\theta)$, DWBA analysis, spectroscopic factors.]

I. INTRODUCTION

It has been found in the past few years that certain single-nucleon transfer reactions induced by heavy ions cannot be reproduced with distorted wave Born approximation (DWBA) calculations if the "normal" procedure is adopted in these calculations,[1,2] i.e., if the same optical model parameters are used for the calculation of both incident and exit channel distorted waves. This procedure gives good agreement between experiment and theory in the overwhelming majority of single-nucleon transfer reactions. However, in the few cases mentioned above the lack of agreement is quite obvious. Oscillations in the measured angular distributions are out of phase with DWBA calculations (these angular distributions are called "anomalous" in the literature).

Single-nucleon transfer reactions which exhibit these features involve mainly transitions between the 1p orbit and the 2s orbit, i.e., the transferred angular momentum l is uniquely equal to unity. A compilation of those reactions [1] led to the conclusion that anomalous angular distributions should show up in a particular reaction only if the incident channel wave number k is within a certain k window (3.5 fm$^{-1} \lesssim k \lesssim$ 5.0 fm^{-1}). However, no l = 1 reaction has been studied so far for k values both within and beyond this k window in order to test this conclusion. In this paper we report an investigation of the l = 1 single nucleon transfer reaction ^{28}Si(^{10}B, ^{9}Be)^{29}P$_{g.s.}$ ($\frac{1}{2}^+$) measured at incident energies E = 59, 75, and 132 MeV. The corresponding k values are 3.92, 4.42 and 5.87 fm^{-1}, respectively. Therefore, a test of the conclusions given in Ref. 1 should be possible.

II. EXPERIMENTAL METHODS AND RESULTS

Self-supporting SiO$_2$ targets (approximately 300 μg/cm^2 thick) were bombarded with the ^{10}B beam of the Texas A & M variable energy cyclotron. The detected particles were identified with a counter telescope consisting of two surface barrier detectors. An energy resolution of approximately 300 keV allowed separation between transitions to the first three states in the residual nucleus ^{29}P. Excited states of the ejectile are particle unstable. Estimated errors in absolute cross sections were about 20% due to uncertainties in target thickness measurements and charge collection in the Faraday cup.

Figures 1–5 show the experimental results. The first three figures exhibit elastic data and angular distributions of the l = 1 transfer reaction leading to the $J^\pi = \frac{1}{2}^+$ ground state of ^{29}P. Figures 4 and 5 show angular distributions for the transitions to the $J^\pi = \frac{3}{2}^+$ and $J = \frac{5}{2}^+$ states in ^{29}P at 1.38 and 1.95 MeV, respectively. The l = 1 transfer

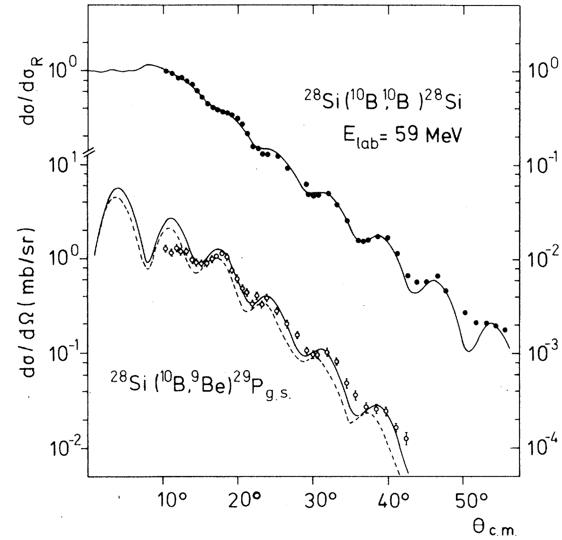

FIG. 1. Angular distributions of the elastic scattering ^{10}B+^{28}Si (upper part) and of the l = 1 transfer reaction ^{28}Si(^{10}B, ^{9}Be)^{29}P$_{g.s.}$ ($\frac{1}{2}^+$) (lower part) measured at E_{lab} = 59 MeV. The solid line in the upper part is an optical-model calculation. The solid and the dashed lines in the lower part are EFR-DWBA calculations. (See text for details.)

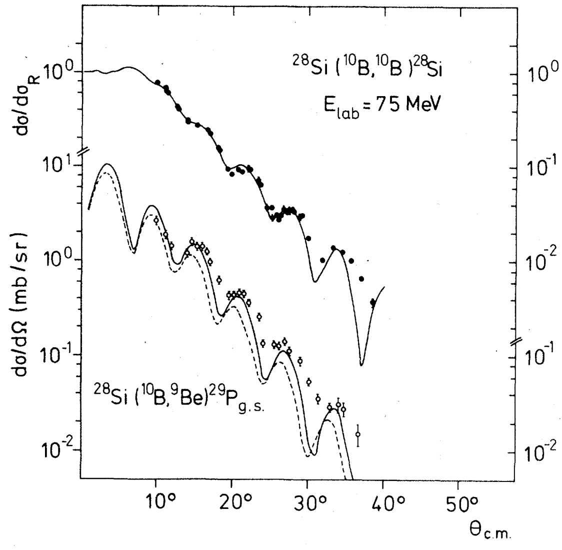

FIG. 2. See legend of Fig. 1. The incident energy is 75 MeV.

data show pronounced oscillations which are in phase with oscillations in the elastic channel.

III. DWBA ANALYSES

Exact finite range DWBA calculations including recoil effects (EFR-DWBA) have been performed for the transfer reactions shown in Figs. 1–5. The program used for this purpose was SATURN-MARS.[3] The post representation without inclusion of Coulomb terms in the form factor was chosen. The popular set $r_0 = 1.25$ fm, $a_0 = 0.65$ fm, and $V_{so} = 6$ MeV for the bound-state parameters was used. Optical-model parameters were deduced from fits to the elastic data. The elastic data at 59 and 75 MeV could be reproduced with the same

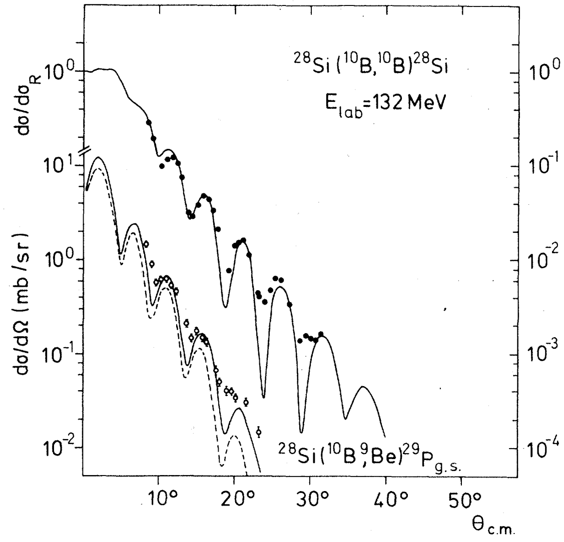

FIG. 3. See legend of Fig. 1. The incident energy is 132 MeV.

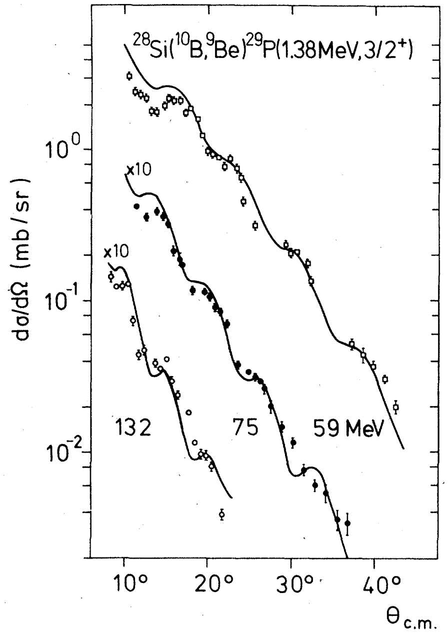

FIG. 4. Angular distributions of the reaction ^{28}Si(^{10}B, ^{9}Be)^{29}P(1.38 MeV, $\frac{3}{2}^+$) measured at $E_{lab} = 59$, 75, and 132 MeV. The solid lines are EFR-DWBA calculations.

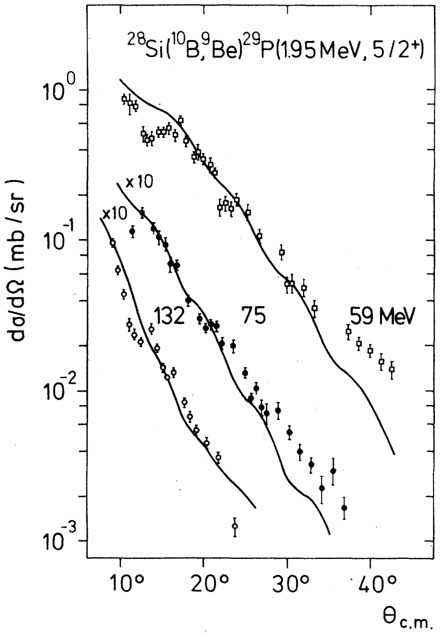

FIG. 5. Angular distributions of the reaction ^{28}Si(^{10}B, ^{9}Be)^{29}P(1.95 MeV, $\frac{5}{2}^+$) measured at $E_{lab} = 59$, 75, and 132 MeV. Solid lines are EFR-DWBA calculations.

TABLE I. Optical-model parameters for $^{10}B + ^{28}Si$.

E (MeV)	V (MeV)	r_{0r} (fm)	a_r (fm)	W (MeV)	r_{0i} (fm)	a_i (fm)
59	100	0.977	0.728	18.03	1.223	0.752
75	100	0.996	0.715	18.03	1.194	0.852
132	63.37	0.915	0.988	13.93	1.271	0.798

set of parameters ($V = 100$ MeV, $r_{0r} = 0.989$ fm, $a_r = 0.7$ fm, $W = 18.03$ MeV, $r_{0i} = 1.198$ fm, $a_i = 0.786$ fm). The smallest χ^2 values, however, were obtained with two slightly different sets (see Table I). The results of these calculations are shown in Figs. 1 and 2 (solid lines in the upper parts). In order to reproduce the 132 MeV elastic data a different parameter set had to be used (see Table I). The solid line in Fig. 3 (upper part) represents the optical model results.

The EFR-DWBA calculations have been performed with the optical-model parameters given in Table I. The same parameters have been used for the calculation of the distorted waves in the incident and exit channel. Figures 1–3 show the calculations for the $l = 1$ transition (solid lines, lower part). Figures 4 and 5 show the results for the $J^\pi = \frac{3}{2}^+$ and $\frac{5}{2}^+$ states, respectively.

IV. DISCUSSION

Inspection of Figs. 1–3 shows that EFR-DWBA calculations and experimental angular distributions for the unique $l = 1$ transition are in rather good agreement. This was expected for the 132 MeV data (Fig. 3) on the basis of the survey of Ref. 1, since the incident channel wave number is larger than 5.0 fm^{-1}. The agreement in case of the 59 and 75 MeV data (Figs. 1 and 2) is, however, quite unexpected since the corresponding k values ($k = 3.92$ and 4.42 fm^{-1}, respectively) are well within the k window for which anomalous angular distributions should exist. Furthermore, reactions involving the same projectile-ejectile combination[4] ($^{12}C(^{10}B, ^{9}Be)^{13}N(\frac{1}{2}^+)$, $k = 3.8$ fm^{-1}) or targets in the same mass region[5] [for instance[6] $^{28}Si(^{13}C, ^{12}C)^{29}Si_{g.s.}(\frac{1}{2}^+)$, $k = 4.8$ fm^{-1}] exhibit anomalous angular distributions for comparable k values. In particular, $l = 1$ single-nucleon transfer reactions in the silicon region are believed to be candidates for anomalous angular distributions due to the existence of coupled-channel effects[7] which are not properly taken into account by normal single-step DWBA calculations.

Another point should be mentioned in connection with the present data: Analyses of $l = 1$ transfer reactions have shown that anomalies are connected with a strong sensitivity of the $l = 1$ transition amplitude on the optical-model parameters used[1]. This sensitivity depends on the special form of the $l = 1$ transition amplitude. It has been shown in Refs. 1 and 8 that small changes in the exit channel parameters can result in dramatic changes in the EFR-DWBA calculations (reorientation of the relative strengths of the two m substate partial cross sections and shift of the oscillations). Furthermore it is shown in Ref. 1 that this sensitivity can be expected for a particular k range. Thus anomalous angular distributions should be a general feature of $l = 1$ transfer reactions for certain k values. Apparently this sensitivity does not exist in the present case as can be seen in Figs. 1 and 2. The dashed lines represent EFR-DWBA calculations which have been performed with a slightly increased radius parameter r_{0i} of the imaginary potential in the exit channel [$r_{0i}(\text{exit}) = r_{0i}(\text{incident}) + 0.1$ fm]. The same normalization has been used as for the solid lines in Figs. 1 and 2. It is obvious that no dramatic changes occur.

Figures 4 and 5 show the results of the EFR-DWBA calculations for the $J^\pi = \frac{3}{2}^+$ and $\frac{5}{2}^+$ states at

TABLE II. Spectroscopic factors for ^{29}P. Values in parentheses are relative spectroscopic factors.

J^π	Single-particle orbits (a,b)	(A,B)	l transfer	S_2 (59 MeV)	S_2 (75 MeV)	S_2 (132 MeV)	^{29}Si [a]	^{29}P [b]
$\frac{1}{2}^+$	$1p_{3/2}$	$2s_{1/2}$	1	0.22 (1)	0.38 (1)	0.28 (1)	0.53 (1.00)	(1)
$\frac{3}{2}^+$	$1p_{3/2}$	$1d_{3/2}$	1,2,3	0.32 (1.45)	0.70 (1.84)	0.28 (1)	0.74 (1.40)	(1.29)
$\frac{5}{2}^+$	$1p_{3/2}$	$1d_{5/2}$	1,2,3	0.06 (0.29)	0.12 (0.32)	0.07 (0.25)	0.12 (0.23)	(0.24)

[a] From the reaction $^{28}Si(d,p)^{29}Si$, Ref. 10.

[b] From the reaction $^{28}Si(d,n)^{29}P$, Ref. 11.

1.38 and 1.95 MeV, respectively. The agreement with the experimental data is quite satisfactory in all cases.

Table II contains the spectroscopic information obtained from the normalization of the EFR-DWBA calculations to the experimental data. From the normalization factor $C_1^2S_1C_2^2S_2$ the spectroscopic factor S_2 for $^{29}\mathrm{P}={}^{28}\mathrm{Si}+p$ has been deduced assuming $S_1=1.2004$ for $^{10}\mathrm{B}={}^{9}\mathrm{Be}+p$ as given by Cohen and Kurath.[9] It is obvious from Table II that the S_2 values deduced at 59 and 132 MeV are almost identical. The S_2 values deduced at 79 MeV are larger than at the other two energies by a factor of approximately 2 but agree rather nicely with S_2 values for the $J^\pi=\frac{1}{2}^+$, $\frac{3}{2}^+$, and $\frac{5}{2}^+$ states in ^{29}Si deduced from the reaction[10] $^{28}\mathrm{Si}(\vec{d},p)^{29}\mathrm{Si}$. It is not clear if this difference has a physical meaning or if it is simply due to the uncertainties involved in this method. The relative spectroscopic factors for the $J^\pi=\frac{1}{2}^+$, $\frac{3}{2}^+$, and $\frac{5}{2}^+$ states agree at all three energies rather nicely with values deduced from the reaction[11] $^{28}\mathrm{Si}(d,n)$ ^{29}P (last column of Table II).

In summary, we have studied the $l=1$ single nucleon transfer reaction at different incident energies ($k=3.92$, 4.42 and 5.87 fm^{-1}). In addition, transitions involving the transfer of several l values were studied. It was found that EFR-DWBA calculations reproduce both oscillations and absolute magnitude of the measured angular distributions. This agreement is unexpected in the case of the $l=1$ transfer and incident channel wave numbers $k=3.92$ and 4.42 fm^{-1} according to predictions deduced from a survey of $l=1$ single-nucleon transfer reactions.[1] Our measurements show that the incident channel wave number is not a parameter which uniquely determines whether a reaction yields normal or anomalous angular distributions. They also show that channel-coupling effects which exist most probably in the present case must not necessarily result in anomalous distributions and that the same projectile-ejectile system can yield both types of angular distributions. This means, however, that the reasons for the occurence of anomalous angular distributions are still not understood.

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*Permanent address: Physikalisches Institut der Universität Erlangen-Nürnberg, D-8520 Erlangen, W. Germany.

[1] K.-I. Kubo, K. G. Nair, and K. Nagatani, Phys. Rev. Lett. 37, 222 (1976); also Cyclotron Institute Progress Report, Texas A & M University, 1976 (unpublished).

[2] P. D. Bond, C. Chasman, J. D. Garrett, C. K. Gelbke, Ole Hansen, M. J. LeVine, A. Z. Schwarzschild, and C. E. Thorn, Phys. Rev. Lett. 36, 300 (1976).

[3] T. Tamura, Phys. Rep. 14C, 59 (1974).

[4] K. G. Nair, H. Voit, M. Hamm, C. Towsley, and K. Nagatani, Phys. Rev. Lett. 33, 1588 (1974).

[5] D. Dehnhard, J. L. Artz, D. J. Weber, and V. Shkolnik Phys. Rev. C 13, 164 (1976); I. Tserruya, W. Bohne, P. Braun-Munzinger, C. K. Gelbke, W. Grochulski, H. L. Harney, and J. Kusminski, Nucl. Phys. A242, 345 (1975).

[6] J. F. Petersen, K. A. Erb, and S. J. Willett, in Proceedings of the International Conference on Nuclear Structure, Tokyo, Japan, 1977 (unpublished).

[7] L. Ray and W. R. Coker, Phys. Rev. C 13, 1367 (1976).

[8] K. G. Nair and K.-I. Kubo, Phys. Rev. C 15, 1774 (1977).

[9] S. Cohen and D. Kurath, Nucl. Phys. A101, 1 (1967).

[10] M. C. Mermaz, C. A. Whitten, J. W. Champlin, A. J. Howard, and D. A. Bromley, Phys. Rev. C 4, 1778 (1971).

[11] S. G. Buccino, D. S. Gemmel, L. L. Lee, J. P. Schiffer, and A. B. Smith, Nucl. Phys. 86, 353 (1966).