Excitation Functions for Single-Nucleon Transfer Reactions Close to the Barrier

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Thick targets of KI, RbCl, ZnS, and Al were bombarded with 27.5-MeV N^{14} ions and excitation functions were obtained for the following single-nucleon transfer reactions: $K^{39}(N^{14},O^{15})Ar^{38}$; $Cl^{35}(N^{14},O^{15})S^{34}$; $Cl^{35}(N^{14},N^{15})Cl^{34m}$; $S^{32}(N^{14},O^{15})P^{31}$; and $Al^{27}(N^{14},O^{15})Mg^{26}$. The proton transfer reactions were identified by the annihilation radiation due to the O^{15} (2.1 min) positrons; the neutron transfer reaction was identified by the characteristic 145-keV γ ray of Cl^{34m} (32.4 min). The cross sections at 27.0 MeV (lab) were found to be: 0.35, 1.35, 0.73, 1.55, and 0.45 mb for the reactions in the order listed above. Single-nucleon transfer excitation functions at low bombarding energies, available from previous works, were accumulated and examined from the standpoint of the tunneling theory. It was found that reactions involving the targets B^{10} and N^{14} invariably behave anomalously. Explanations of this behavior are offered. The ratios of reduced widths for the transferring neutron in N^{14} and F^{19} were determined from four pairs of reactions. These four ratios, which should be identical, agree to within a factor of 3. The "universal curve" noted earlier for transfer reactions was found to be invalid when all the available data were considered.

INTRODUCTION

THE study of single-nucleon transfer reactions in the field of heavy-ion interactions is prompted by the need for information concerning the nuclear surface. Specifically, these reactions should ultimately result in a knowledge of the reduced widths of the transferring nucleon in both the initial and final states.[1,2]

Previous determinations of total cross sections for single-nucleon transfer reactions involving N^{14} ions have dealt extensively with reactions in which the incident particle transfers a neutron to the target nucleus and in the process becomes N^{13}. This latter isotope has a 10-min half-life and provides a convenient method of obtaining total and, in some cases, differential cross sections. These reactions have been studied near the Coulomb barrier[3–13] and at energies well above the barrier.[14–17] Recently, neutron transfer reactions induced by F^{19} ions have been investigated by Perkin *et al.*[18] These reactions involved the transfer of a neutron from the incident F^{19} to the target nucleus, and the reactions were studied by taking advantage of the resultant F^{18} radioactivity.

From a survey of previous work, it becomes evident that little information exists concerning cross sections for transfers in which a proton rather than a neutron is the transferred particle, and in which the nucleon is transferred from the target to the incident nucleus. In the present investigation four additional excitation functions were obtained for transfer reactions fulfilling both conditions listed above, and a fifth involving the transfer of a neutron fulfilling the second condition.

In N^{14}-induced transfer reactions where the N^{13} is the detected particle a stringent restriction is necessarily imposed, i.e., the observed N^{13} nuclei must have been formed in their ground states since N^{13} excited states are unstable with respect to particle emission. The corollary is, therefore, that transfers proceeding to the N^{13} excited states are never observed. In the five reactions investigated here, excited states in both residual nuclei are stable; thus, in all instances the transfer cross section is measured for many states in each nucleus.

EXPERIMENTAL PROCEDURE

Thick targets of Al, ZnS, RbCl, and KI were bombarded with triply charged N^{14} ions accelerated in the Oak Ridge 63-in. cyclotron. The N^{14} incident energy was measured to be 27.5±0.4 MeV as determined by the method of Halbert and Zucker.[19] The bombarding energy was varied by inserting appropriate nickel absorbers into the beam. By placing the nickel absorbers and the target directly in a Faraday cup, electron loss by the initial beam while traversing the nickel foils

* Operated for the U. S. Atomic Energy Commission by Union Carbide Corporation.

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did not have to be considered and the integrated current could be converted to the number of incident particles without ambiguity. An experimental range curve for N^{14} ions in nickel, published previously,[20] was used to determine the energy loss suffered by the N^{14} beam for a given absorber. Finely pulverized ZnS, RbCl, and KI were pressed into $\frac{3}{4}$-in.-diam brass molds with a hydraulic press and then placed in the Faraday cup. Aluminum targets consisted of metal foils which were set directly in the bombarding assembly. The targets prepared in this manner were of sufficient thickness to stop the incident ions. No reactions were possible with the elements Zn, Rb, and I because of their high Coulomb barrier.

After bombardment the assembly was removed from the scattering chamber, and the irradiated material was carefully removed from the mold, placed in a counting cup, and set directly on a 3-in.×3-in. NaI crystal connected to a 256-channel pulse-height analyzer. The time lapse between the end of bombardment and the beginning of counting was usually about one minute. The proton transfer reactions were identified by obtaining the decay curve of the annihilation radiation peak and identifying the 2.1-min β^+ activity of O^{15}. The only other β^+ emitter in this region of the periodic table that could cause possible confusion is P^{30} (2.5 min). The targets were selected so that P^{30} would not be formed at all or with yield which was less than our estimated error. The neutron transfer reaction $Cl^{35}(N^{14},N^{15})Cl^{34m}$ was detected by taking advantage of the characteristic 145-keV γ ray belonging to the 32.4-min Cl^{34m} decay. From the discussion it is clear that chemical separations were not needed to assist the identification of O^{15} and Cl^{34m}. As a precaution, the targets were stored in a desiccator prior to bombardment to prevent the accumulation of moisture in the targets since the excitation function for the reaction $O^{16}(N^{14},O^{15})N^{15}$ has not been determined.

The 3-in.×3-in. NaI crystal was calibrated for the particular counting geometry by the use of several γ-ray standards. A relative photopeak efficiency curve was constructed from the known decay characteristics[21] of Na^{22}, Sc^{46}, Co^{58}, Fe^{59}, Co^{60}, Zn^{65}, Y^{88}, Cd^{115m}, and Sb^{125}. In this way the γ-ray energy region below 1.8 MeV was covered. This curve could then be made absolute by determination of the absolute disintegration rate of one or more of the samples. Three sources, Na^{22}, Co^{58}, and Zn^{65}, were β counted in a shielded Geiger counter with a known counting efficiency to provide this calibration. The error in the absolute photopeak efficiency is estimated to be ±14%. In all of the investigated reactions the absolute γ-ray counting rate was corrected for the decay during bombardment and for beam intensity to obtain the absolute yields per incident particle. A branching ratio of 33% was used for the 145-keV Cl^{34m} γ ray.[21]

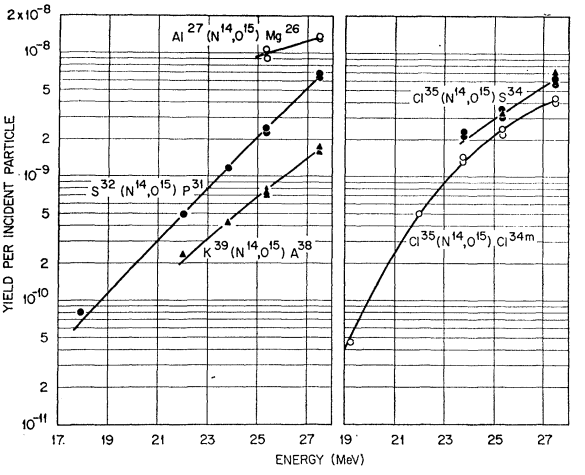

FIG. 1. Thick-target yields determined for the investigated transfer reactions. For the reaction, $Cl^{35}(N^{14},O^{15})S^{34}$, the closed dots show the data obtained with targets containing natural abundance chlorine; the closed triangles represent the data from targets enriched in Cl^{35}.

RESULTS

The thick-target yields per incident particle determined as a function of bombarding energy are shown in Fig. 1. The scatter in the experimental points illustrates the relative experimental error; this error arises from uncertainties in beam intensity, counting statistics, and variation of the incident N^{14} energy. Smooth curves were drawn through the data points and, by differentiating these curves, the cross sections were obtained as a function of the incident energy. For this determination the stopping powers were calculated in a manner previously described.[22] The probable error in the absolute cross sections is estimated to be about ±30%, taking into account uncertainties in crystal calibration, slope of the yield curve, and in the stopping power. The excitation functions are shown in Fig. 2.

For the proton transfer reaction where Cl^{35} is assumed to be the target nucleus, there is the possibility that some of the resultant O^{15} may be produced from the same reaction on Cl^{37} (24.47% of natural abundance chlorine). Targets of AgCl, enriched in Cl^{35} to 95%, were bombarded at two energies. The yield points, shown as triangles in Fig. 1, show that the yields from the enriched targets agree, within experimental errors, with those obtained for the natural abundance targets. It was assumed, therefore, that the observed O^{15} is due to Cl^{35} and not to Cl^{37}.

The cross-section data indicate the general characteristics of single-nucleon transfer reactions. The order of magnitude of the cross sections (from a few tenths

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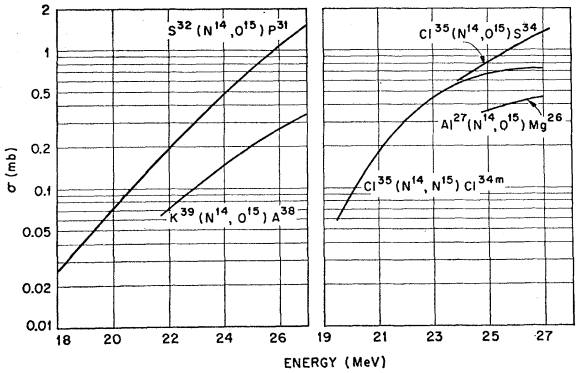

FIG. 2. Excitation functions obtained for the investigated transfer reactions.

to 1 or 2 mb) is the same as observed earlier for this range of N^{14} bombarding energies. The excitation functions are less steep, close to and below the barrier, than for reactions proceeding through a compound nucleus. Transfers do not require the amalgamation of the interacting nuclei, and, therefore, are expected to occur at energies for which the compound nucleus is difficult to form.

DISCUSSION

The tunneling theory of Breit and collaborators[1,2,23,24] is a description of the mechanism of neutron transfer reactions below the Coulomb barrier. This theory treats the initial and final nuclei by assuming they are traveling on classical Rutherford orbits and the motion of the neutron which is tunneling between the two nuclear surfaces is treated quantum mechanically. In addition to predicting the shape of the angular distributions for transfer reactions, an expression was derived for the variation of the total cross section with energy. This expression is

$$\sigma=\frac{\Lambda^2}{8}\left(\frac{1}{\alpha\bar{\alpha}\lambda\lambda'}\right)\left[\frac{b_1b_2}{(1+\alpha b_1)(1+\bar{\alpha}b_2)}\right]^2\exp(x), \quad (1)$$

where

$$x=\frac{(2M)^{1/2}}{\hbar}\left[(b_1+b_2)E_s^{1/2}\left(1-\frac{E_B}{E}\right)+(\bar{b}_1+\bar{b}_2)\bar{E}_s^{1/2}\left(1-\frac{\bar{E}_B}{\bar{E}}\right)\right]; \quad (2)$$

b_1 and b_2 = radii of initial and final nuclei 1 and 2, respectively; $\Lambda=h/Mv$ = reduced wavelength of the transferred neutron, v = relative velocity, E_s = binding energy of the neutron, $\alpha=(2ME_s/\hbar)^{1/2}$, M = neutron mass, $E_B=Z_1Z_2e^2/1.5(A_1^{1/3}+A_2^{1/3})$ = Coulomb barrier, E = center-of-mass energy, and the unbarred and barred quantities refer to the initial and final systems, respectively. Besides the various kinematical factors, the cross-section expression contains the product of the reduced widths of the neutron in the two participating nuclei, $\lambda\lambda'$, where λ refers to the nucleus donating the neutron and λ' refers to the nucleus which has accepted the transferred neutron. Specifically for the case $B^{10}(N^{14},N^{13})B^{11}$, λ refers to the neutron reduced width in N^{14}, while λ' refers to the B^{11}. The probability of finding the neutron in a shell of unit thickness around one of these nuclei is proportional to the reciprocal of the appropriate λ.

To facilitate comparison between theory and experiment, the excitation functions can be plotted as $\log(4\pi^2\sigma/\Lambda^2)$ vs x. In the region where the tunneling theory is applicable ($E<E_B$), it predicts that x should change by a factor of ln10 for an order of magnitude change in σ/Λ^2.

The avilable experimental data have been grouped into three sections: (1) N^{14}-induced reactions producing N^{13} as one of the reaction products, (2) F^{19}-induced transfers resulting in F^{18}, and (3) the reactions investigated in this work together with two single-proton transfers studied earlier. These data are plotted in Fig. 3. Although the excitation functions as plotted obviously do not all have the same slopes, there is a tendency for the heavier target data to fall on straight lines that group together and have rather similar slopes close to the value predicted by the tunneling theory. Two targets, B^{10} and N^{14}, behave anomalously in all three sets of data, the anomaly being manifested by a slope that is much more gentle than the one predicted by the tunneling theory and/or by a break in the curves. Another reaction, $Cl^{35}(N^{14},N^{15})Cl^{34m}$, involving the detection of the isomer of Cl^{34}, also displays a break in the excitation function.

In angular distribution studies of transfer reactions with 27.5-MeV N^{14} ions on the targets B^{10} and N^{14}, it was found[11,12,25] that transfers leaving both products in their ground states account for approximately half of the total cross section. It was also shown[11,12] for the N^{14} target that when the bombarding energy was lowered to 20 MeV the transfers left the residual nuclei predominantly in excited states.[26]

It is possible that the variation of final-state population with energy and the wide spacing of the low-lying states in the low-Z region may account for the observed breaks in the B^{10} and N^{14} curves. In an attempt to remove the break for the reaction $N^{14}(N^{14},N^{13})N^{15}$, different Q values were used for the two portions of the curve in Fig. 3: 0.29 and −5.00 MeV. The two Q values correspond to the N^{15} being left in its ground state and in its first excited states, respectively. When these Q values were used, it was found that the curve did indeed straighten out. Alternately, the possibility of accounting

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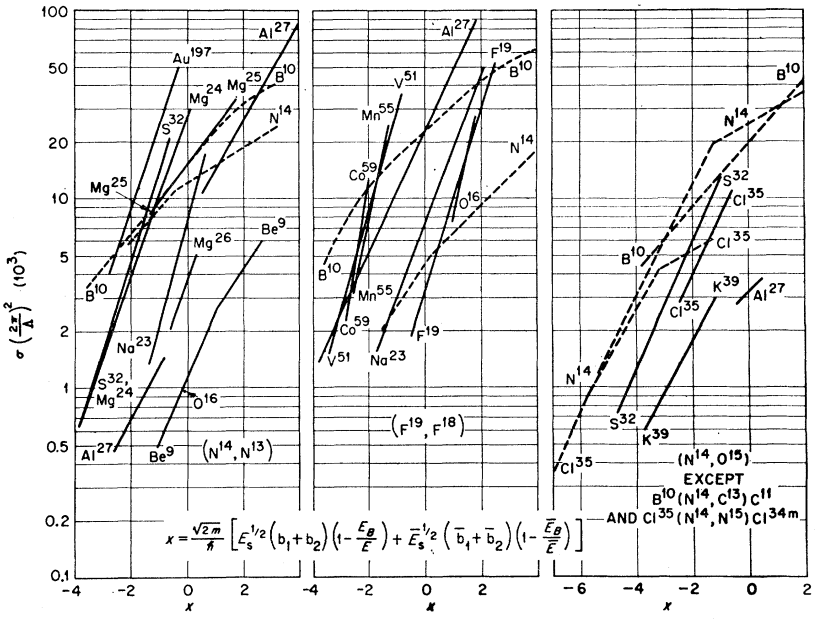

FIG. 3. Single-nucleon cross-section data plotted as $4\pi^2\sigma/\Lambda^2$ vs x; $\Lambda = h/Mv$ = the reduced wavelength of the transferred nucleon; x = the quantity shown in the figure. The figure is divided into three portions as follows: at the left (N^{14},N^{13}) transfers, in the center (F^{19},F^{18}) transfers, and to the right the present data together with two proton transfers studied earlier. The curves are labeled according to the bombarded target.

for the anomalous behavior of the B^{10} and N^{14} reactions by virtual Coulomb excitation was suggested by Breit.[2]

There are four pairs of reactions in which the same target nucleus has been bombarded with both N^{14} and F^{19} beams. The product $\lambda\lambda'$ can be extracted from the value of $4\pi^2\sigma/\Lambda^2$ at the point where $x=0$. For the above-mentioned pairs, however, because of the identical targets, four independent values of the ratio, $\lambda(N^{14})/\lambda(F^{19})$, can be obtained. Naturally, these four ratios must be identical and serve as a test as to how well the λ's may be extracted from the curves. In Table I the reactions, $\lambda\lambda'$ products, and the $\lambda(N^{14})/\lambda(F^{19})$ ratios are listed. Changing the barrier energy (using $r_0=1.3$ or 1.7 rather than 1.5) alters the value of the $\lambda\lambda'$ products but does not seriously affect the value of the ratios. Two entries are shown for the $Al^{27}(N^{14},N^{13})Al^{28}$ reaction. The values shown are straight line extrapolations of the data of references 14 and 7, respectively. The measurements of reference 7 exist only below $x=0$, while those of reference 14 were made at energies above $x=0$. Of the two $\lambda\lambda'$ products the one deduced from reference 14 yields a $\lambda(N^{14})/\lambda(F^{19})$ ratio which is closer to those derived from the remaining three pairs of reactions. It must be remarked, however, that both sets of data, references 7 and 14, involve large experimental errors. In reference 7 the measured cross section is extremely low, while in reference 14 the uncertainty in the N^{14} beam energy was approximately 10 MeV. While the agreement between the four sets of ratios is not spectacular, it is gratifyingly close, especially since only kinematical factors and no detailed nuclear structure

TABLE I. Reduced widths.

Reaction pair	$\lambda\lambda'$ (10^{-24} cm²)	$\lambda(N^{14})/\lambda(F^{19})$
$N^{14}(N^{14},N^{13})N^{15}$	2.20	0.37
$N^{14}(F^{19},F^{18})N^{15}$	5.98	
$B^{10}(N^{14},N^{13})B^{11}$	1.61	1.44
$B^{10}(F^{19},F^{18})B^{11}$	1.12	
$Na^{23}(N^{14},N^{13})Na^{24}$	4.03	0.88
$Na^{23}(F^{19},F^{18})Na^{24}$	4.56	
$Al^{27}(N^{14},N^{13})Al^{28}$	4.05[a]:12.2[b]	2.77[a]:7.36[b]
$Al^{27}(F^{19},F^{18})Al^{28}$	1.46	

[a] See reference 14.
[b] See reference 7.

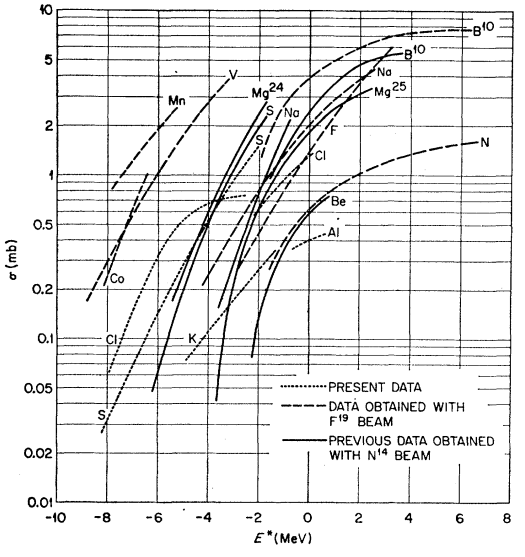

FIG. 4. Single-nucleon transfer cross sections plotted as a function of E^*, where $E^*=E_{c.m.}-E_{barrier}+Q$. Dotted curves represent the five investigated reactions, dashed curves show the data of Perkin *et al.*, while the full curves represent earlier data obtained with N^{14} beams. The curves are labeled according to the bombarded target.

information has been included in the tunneling model.

In an earlier attempt[8] to systematize transfer excitation functions the measured cross sections were plotted vs E^*, where $E^*=E_{c.m.}-E_{barrier}+Q$. The quantity E^* is the kinetic energy available to the system at the time of contact after the transfer has occurred. Excitation functions plotted in this manner, with a few exceptions, tended to group together. These exceptions, Mg^{24}, Be^9, and C^{12}, gave the curve a banded structure, that is, a main curve flanked by two satellites. It was hoped that with a few exceptions a "universal curve" existed for transfer reactions and that it could be used to predict unknown cross sections by the calculation of the quantity E^*. Fisher *et al.*,[9] at the suggestion of Breit, replotted transfer cross sections vs the expression $[E_{c.m.}-E_{barrier}+Q/2]$. Their "universal curve" brought some excitation functions closer together but displaced others. The over-all curve retained the three bands but the two satellites, now referring to reactions on different targets than in the first plot, were displaced to the same side of the main group.

In Fig. 4 the available single-nucleon transfer cross sections at low incident energies are plotted vs E^*. Dotted curves represent the five excitation functions obtained in this work, dashed curves show the data of Perkin *et al.*,[18] while the solid curves represent the earlier data obtained with N^{14} beams. Not all excitation functions are shown in the diagram because some curves overlap and displaying these would tend to be confusing. A sufficient number of curves is shown, however, so that it is readily seen that in fact no" universal curve" exists. Reactions whose E^* values are about -7 or -8 MeV would have been expected from the earlier "universal curve" to have extremely small cross sections, but are seen to possess cross sections of a few millibarns. Also, instead of being closely grouped, the curves are spread over a wide range of E^*. A trend can be observed from Fig. 4, i.e., the higher the atomic number of the target the higher the cross section for a given value E^*. Plotting the cross sections in the manner of Fisher *et al.*[9] does not bring about any additional clustering around a "universal curve."

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Melting and Polymorphism at High Pressures in Some Group IV Elements and III–V Compounds with the Diamond/Zincblende Structure*

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The fusion curves of several elements and III–V compounds crystallizing in the diamond/zincblende structure have been determined to 50, or sometimes 70, kbar by means of differential thermal analysis. The melting slopes are (in °C/kbar); Si, −5.8 (lower bound); Ge, −3.8; InAs, −4.3; GaAs, −3.4; InP, −2.9; AlSb, −6.9 (provisional); GaSb, −5. Gallium antimonide has a triple point near 56.5 kbar and 385°C; its high pressure metallic polymorph melts with an initial slope of +3.4 °C/kbar. Progressively more negative slopes for the melting of the diamond/zincblende structures are apparently correlated with increasing atomic volume and decreasing normal melting point. Extension of these correlations suggests that diamond melts with only a slightly negative slope. The sequence of pressure-induced polymorphic transitions strikingly reflects straightforward increases in coordination.

I. INTRODUCTION

THE diamond and the related zincblende type structure is a consequence of tetrahedrally coordinated atoms, with predominantly covalent binding. The Group IV elements, germanium and silicon as well as carbon and gray tin, crystallize in such a structure, as do many of the binary equiatomic compounds formed between Group III and V elements.

The semiconducting properties of germanium and silicon especially, and also of the III–V compounds have received a great deal of attention. The band structures of many of these have been explored by a variety of techniques including, recently, the effects of pressure.[1] The study[2] of the electrical properties, for instance, of these semiconductors at moderately high pressures has contributed to the understanding of the conduction mechanisms in terms of pressure coefficients

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