$^{14}N(^{14}N,^{13}N)^{15}N$ Reaction and the Neutron Tunneling Mechanism*

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Angular-distribution and total-cross-section measurements have been made for the $^{14}N(^{14}N,^{13}N)^{15}N$ reaction over a range of energies. For center-of-mass energies below about 6.5 MeV, the tunneling theory of neutron transfer is shown to give a good account of the data. At higher energies, nuclear absorption occurs for the close collisions and spoils the tunneling description. These results show why earlier descriptions of this reaction by the tunneling theory were unsuccessful.

I. INTRODUCTION

As described in the preceding paper,[1] an angular-distribution study of the $^{14}N(^{14}N,^{13}N)^{15}N$ reaction has shown that the tunneling description[2] of the neutron-transfer process is valid at a center-of-mass reaction energy of E(c.m.)=6.62 MeV. Previous experiments[3] at a somewhat higher energy [E(c.m.)=8.15 MeV] had been found to be in disagreement with the tunneling theory[2] even though the reaction energy was still presumably below the Coulomb barrier as in the 6.62-MeV experiment. Further angular-distribution experiments have therefore been carried out at several energies between E(c.m.)=6.62 MeV and E(c.m.)=9.0 MeV to study the transition from tunneling conditions to the breakdown to the tunneling description. The Oak Ridge Tandem Van de Graaff Accelerator was used to supply the variable-energy beam ($\sim$0.2 μA) of ^{14}N ions.

A determined effort was made to study also the reaction at energies below 6.62 MeV because of the expected importance of neutron transfer by virtual Coulomb excitation at the lower energies.[4] Angular distribution measurements were made therefore at center-of-mass energies of 5.50 and 6.15 MeV. Finally, total-cross-section measurements were made over the entire energy range (from 4.7 to 9.4 MeV) to provide an independent and possibly more sensitive check on the range of validity of the tunneling theory particularly at low energies.

II. EXPERIMENTAL PROCEDURE

The experimental apparatus is essentially the same as that described in the preceding paper.[1] The ^{14}N beam, however, was supplied in this work by the Oak Ridge Tandem Van de Graaff Accelerator instead of the Yale University Heavy Ion Accelerator. Also a 20-channel encoder and control system has been added to the experiment at ORNL. The encoder provides for automatic storage of the 20 coincidence outputs from the positron detection system[5] in the memory of a Victoreen 800-channel analyzer. A data pulse at one of the 20 inputs of the encoder initiates a cycle which adds one count to the contents of the proper analyzer channel. The analyzer timer is used to control the subgroup of 20 channels in which the counts are stored. Each time the analyzer timer resets, the beginning address of the 20-channel subgroup is advanced by 20 channels. Typically, forty 1-min intervals are preset on the timer such that counts occurring in the first minute are stored in channels 0–19, in the second minute in

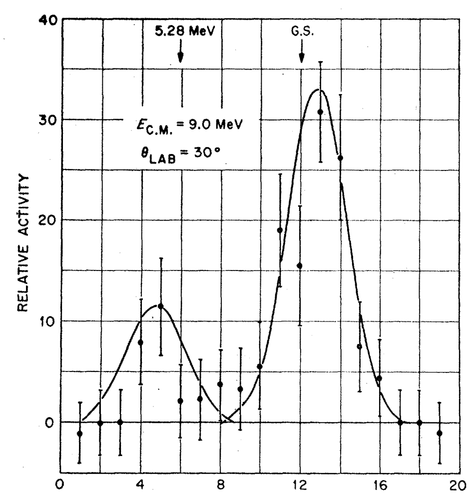

FIG. 1. Range measurement of the ^{13}N ions at a laboratory angle of 30° and a center-of-mass energy of 9.0 MeV. The arrows above the data points indicate the ranges expected for transfers of different Q values corresponding to various excitations of the ^{15}N nucleus.

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[2] G. Breit and M. E. Ebel, Phys. Rev. **103**, 679 (1956).
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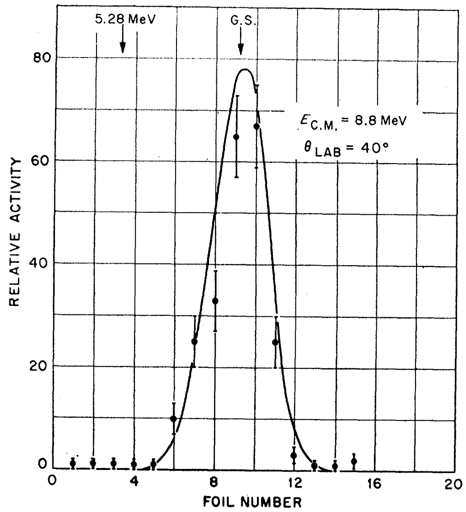

FIG. 2. Same as Fig. 1 except that the laboratory angle is 40° and the center-of-mass energy is 8.8 MeV.

channels 20–39, etc., utilizing the entire analyzer memory.

III. RESULTS AND DISCUSSION

A. The Range Measurements

Range measurements of the ^{13}N ions were made near the center-of-mass energy of 9.0 MeV and at the laboratory angles of 30 and 40°. The results of these measurements are shown in Figs. 1 and 2, respectively. At both angles the main contribution to the transfer process comes from ^{13}N ions leaving the ^{15}N residual nucleus in its ground state. However, at the smaller angle a significant contribution is also found for transfers corresponding to excitation of the ^{15}N nucleus (the shorter range peak in Fig. 1). This result is in agreement with the observations of Toth[6] at somewhat higher energies and is understood qualitatively as being due to a larger deflection being given to the lower energy ^{13}N nuclei. (It should be remembered that in the experiments reported here, the recoil nuclei are being observed at the small angles so that smaller angles correspond to larger deflections.)

The dominance of neutron transfer to the ground state of ^{15}N at 9.0 MeV has been previously noted.[7] Earlier work,[6] however, had indicated an absence of ground-state transfer at this energy. These results therefore confirm the importance of ground-state transfer at 9.0 MeV in this reaction.

The angular-distribution data at 9.0 MeV, as presented in the next section, correspond to neutron transfer to the ground state of ^{15}N. Because of the difficulty of obtaining good range data at the small angles ($d\Omega/d\theta$ vanishes at the small angles), rather large error assignments have been made to these data for the small angle points.

B. Angular-Distribution Measurements

The angular-distribution results[8] are plotted in Figs. 3, 4, 6–8. Figure 5 shows data from the preceding paper.[1] The angular resolution of these data is 5° (full width at half-maximum). The error bars are statistical only except for those at small angles in Fig. 8 (see preceding paragraph). Other sources of error are expected to be negligible in comparison, except for the absolute value of the cross-section scale which is reliable to $\pm 7\%$ (see preceding paper).

The theoretical curves plotted with the data are from the tunneling theory of Breit, Chun, and Wahsweiler (BCW).[9] The dashed curves are the absolute squares of the scattering amplitudes for the projectile and recoil ^{13}N. In most cases they have simply been normalized to the experimental data by eye. These curves represent the cross sections that would be obtained if the projectile and target nucleus were not identical. As would be expected, the cross sections for distant collisions are small so that the cross sections at small scattering angles are small. The square of the sum of the amplitudes yields the differential cross section with its interference pattern. These curves show then that the main contribution to the small-angle data comes from the recoil nuclei, corresponding thus to large-angle scattering.

Inspection of the angular distribution data shows that, at the low energies the tunneling theory fits the experimental data (Figs. 3 and 4). However, as the energy increases (Figs. 5 and 6), the experimental cross section begins to drop below the theory at the small angles (corresponding classically to close collisions for the recoil nuclei). Presumably, absorption of the ^{13}N

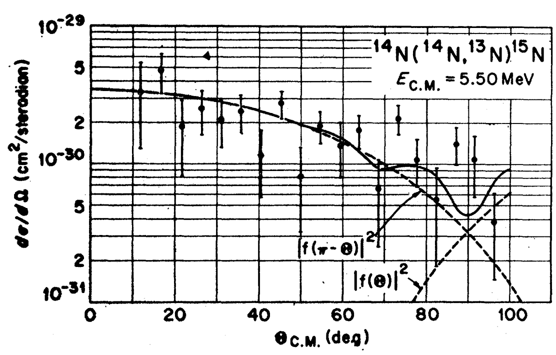

FIG. 3. Angular distribution results at a center-of-mass energy of 5.50 MeV. The points represent experimental measurements. The full curve is the tunneling-theory result of Breit, Chun, and Wahsweiler (Ref. 7) normalized by eye to fit the data. The dashed curves are the squares of the scattering amplitudes $|f(\Theta)|^2$ and $|f(\pi-\Theta)|^2$ corresponding to the cross sections for the projectile and the recoil nucleus if these nuclei were not identical.

[6] K. S. Toth, Phys. Rev. **123**, 582 (1961).

[7] F. C. Jobes and J. A. McIntyre, Phys. Rev. **133**, B893 (1964).

[8] These results are available in tabular form from the authors.

[9] G. Breit, K. W. Chun, and H. G. Wahsweiler, Phys. Rev. **133**, B404 (1964).

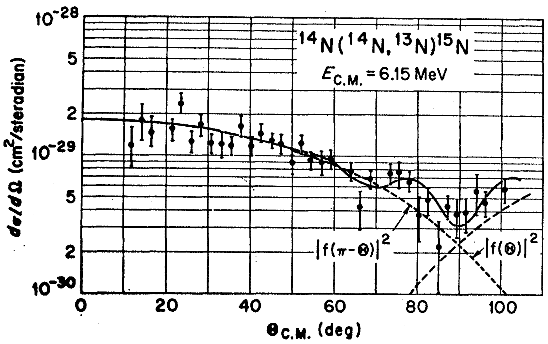

FIG. 4. Same as Fig. 3 except that the center-of-mass energy is 6.15 MeV and a least-squares fit has been made to the data.

nuclei is occurring for collisions inside some nuclear radius. As the energy is further increased (Figs. 7 and 8), the absorption of the ^{13}N extends to larger angles as would be expected for classical Rutherford trajectories. These qualitative features have been accounted for in detail by Polak *et al.*[10] who used reasonable optical-model potentials in a BCW-type tunneling-theory calculation. The failure of the tunneling theory to account for the earlier data of Reynolds and Zucker[3] is thus explained as being due to collisions taking place inside the Coulomb barrier.

Finally, a comparison has been made between two theoretical analyses of the tunneling process[9,11] and the angular distribution data below the Coulomb barrier. A least-squares fit to the data is shown for both theories at 6.15 MeV in Fig. 9. A χ^2 analysis of the fit gives a probability factor of 0.5 for the BCW theory and a probability factor of 0.3 for the Greider theory. Thus both theories are seen to fit the data very well.

C. Total-Cross-Section Measurements

The results[8] of the total-cross-section measurements are plotted in Fig. 10. The accuracy of the measurements has been discussed in the preceding paper[1] where a normalization of earlier data to these data was used to determine the reduced width for the transferred neutron in the $^{14}N(^{14}N,^{13}N)^{15}N$ reaction. In this paper, the total-cross-section data are used only as a test for the validity of the tunneling theory. The accuracy of the cross-section scale is $\pm 7\%$.

Also plotted as a broad band in Fig. 10 are the data of Reynolds and Zucker[3] and the BCW theory[9] normalized to the data below 6.5 MeV by a least-squares

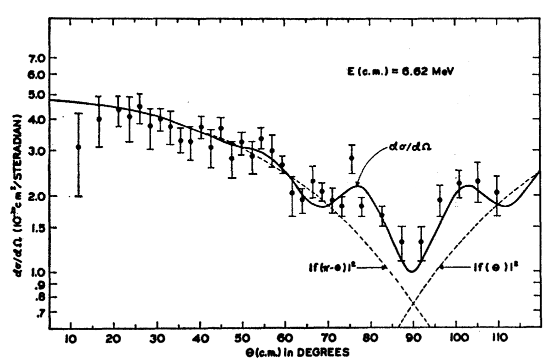

FIG. 5. Same as Fig. 3 except that the center-of-mass energy is 6.62 MeV and the data are from Ref. 1.

[10] J. A. Polak, D. A. Torchia, and H. G. Wahsweiler, Bull. Am. Phys. Soc. 9, 429 (1964). G. Breit, J. A. Polak, and D. A. Torchia, Paper presented at Congrès International de Physique Nucléaire, Paris, France, 2–8 July 1964 (unpublished).

[11] K. R. Greider, Phys. Rev. **133**, B1483 (1964).

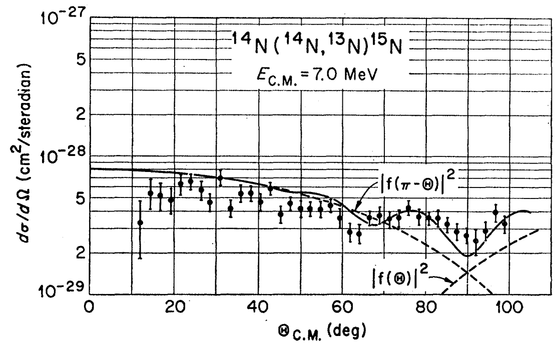

FIG. 6. Same as Fig. 3 except that the center-of-mass energy is 7.0 MeV.

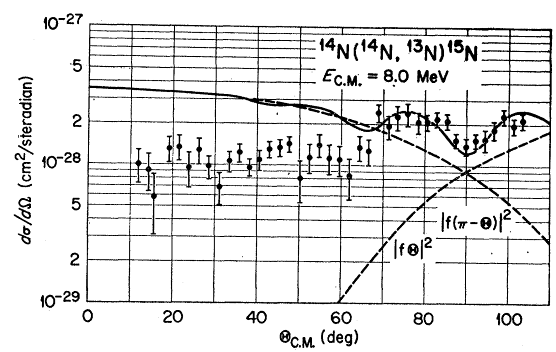

FIG. 7. Same as Fig. 3 except that the center-of-mass energy is 8.0 MeV.

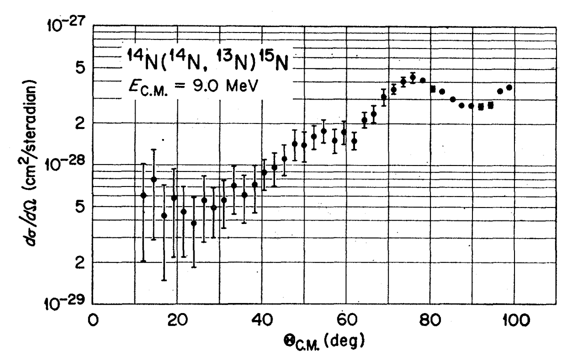

FIG. 8. Same as Fig. 3 except that the center-of-mass energy is 9.0 MeV.

fit. A χ^2 test of the fit yielded a probability factor of 0.1 which indicates quite good agreement between the theory and experiment. However, at energies above 7 MeV, the experimental data begin to fall below the tunneling curve. This result is consistent with the angular-distribution data, where deviations from the tunneling theory become significant at about 7 MeV as the effects of nuclear absorption become important. As the energy is increased further, more nuclear absorption occurs and the data fall far below the theory. Comparison of the data to the earlier Reynolds–Zucker work shows agreement at the higher energies but a considerable discrepancy at the lower energies.

At the low-energy end of the total-cross-section curve the statistical fit between the BCW theory and the data is good. Nevertheless, the five lowest energy points all lie above the curve and this may indicate that some additional transfer process such as virtual Coulomb excitation[4] is beginning to become significant.

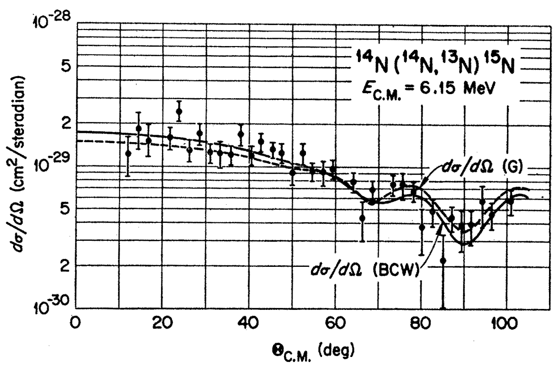

FIG. 9. Angular distribution data at E(c.m.) = 6.15 MeV plotted with the BCW (Ref. 7) tunneling theory and Greider (Ref. 9) tunneling theory. The two tunneling-theory curves are normalized by least-squares fits to the experimental points. χ^2 tests of the fits yield a probability factor of 0.5 for the BCW curve and a probability factor of 0.3 for the Greider curve.

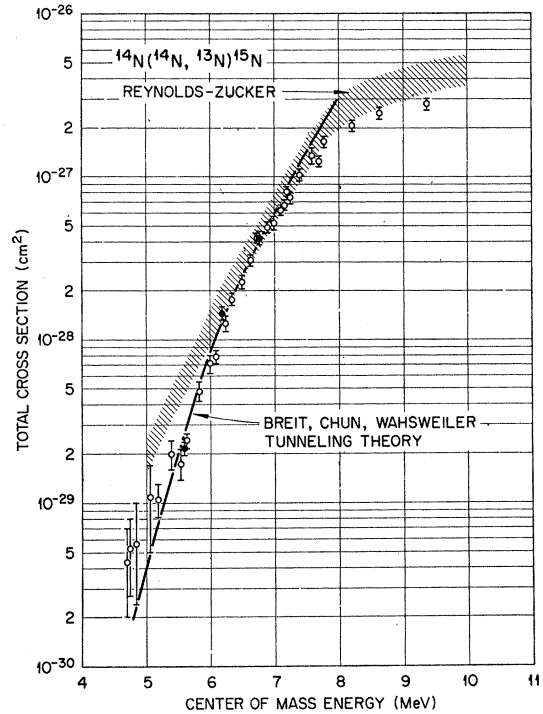

FIG. 10. Total-cross-section results. The points represent experimental measurements. The full curve is the tunneling theory of BCW (Ref. 7) normalized to the experimental points below 6.5 MeV by a least-squares fit. A χ^2 test yields a probability factor of 0.1 for the points below 6.5 MeV. The cross-hatched band represents the data of Reynolds and Zucker (Ref. 3). The data shown as solid points were taken with a ^{14}N gas target. All other points were taken with adenine targets.

IV. CONCLUSIONS

The data presented here show that the tunneling theory[9,11] is a good description of the neutron-transfer reaction $^{14}N(^{14}N,^{13}N)^{15}N$ at energies below the Coulomb barrier. At higher energies, the cross section becomes attenuated at angles corresponding to particle trajectories describing close collisions.

The origin of the discrepancies between the tunneling theory and experiment in earlier work[2,3] has now become clear. The angular-distribution discrepancy at 8.15 MeV was caused by the importance of nuclear absorption at that energy. The discrepancy in the ratio of the total cross sections at 7.5 and 5.0 MeV was caused by (1) nuclear absorption at 7.5 MeV and (2) high experimental cross sections at 5.0 MeV.

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