reactions, $Sc^{45}(\alpha,\alpha n)Sc^{44}$ or $Sc^{45}(p,pn)Sc^{44}$, are summarized below:

Neutron levels	$1f_{7/2}$, $1d_{3/2}$, $2s_{1/2}$	$1f_{7/2}$, $1d_{3/2}$, $2s_{1/2}$, $1d_{5/2}$
Sc^{44m}/Sc^{44}		
for spins 7, 3	0.46	0.56
for spins 6, 2	1.4	1.5

It is observed that the calculated isomer ratio, 0.46 or 0.56, from the knock-on calculation agrees fairly well with the experimental isomer ratio 0.62 for 320-Mev helium ions. The agreement between the calculated and experimental yield ratios of Sc^{44m}/Sc^{44} for the K^{41}(10-Mev α,n)Sc^{44} reaction, which was assumed to proceed by a compound-nucleus mechanism, and for the Sc^{45}(320-Mev α, αn)Sc^{44} reaction, which was assumed to occur by a knock-on mechanism, indicate the usefulness of these methods for calculating isomer ratios from nuclear reactions. Katz[6] used a compound-nucleus model to calculate isomer ratios from nuclear reactions and obtained agreement between calculated and experimentally measured ratios, and Rudstam[24] used the Serber[25] model and made Monte Carlo cascade calculations to calculate an isomer ratio in general agreement with experiment.

ACKNOWLEDGMENT

I wish to express my gratitude to Professor Isadore Perlman, under whose guidance this work was done.

[24] Gösta Rudstam, thesis, University of Uppsala, 1956 (unpublished).
[25] R. Serber, Phys. Rev. **72**, 1114 (1947).

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Angular Distribution and Ranges of N^{13} Particles from N^{14} on N^{14}

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The distribution of N^{13} particles from the neutron transfer reaction $N^{14}(N^{14},N^{13})N^{15}$ was investigated from 3.5–32° in the laboratory. Range curves for N^{13} particles were obtained from 16–32° (laboratory system). Transfers leaving both residual nuclei in their ground states were distinguished from those in which the products are left in excited states. It is found that (1) the ground-state transfer cross section decreases as the bombarding energy is lowered; (2) of the N^{15} excited states, only the first and/or second contribute significantly to the transfer cross section; (3) for a given bombarding energy the excited-state transfer distribution peaks at an angle larger than that at which the ground-state transfer distribution reaches its maximum; (4) from the ground-state transfer distribution an r_0 of 2.2 f can be determined, while the excited-state transfer distribution yields an r_0 of about 1.65 f; and (5) the excited-state distributions are more consistent with the tunneling mechanism of Breit and Ebel than are the ground-state distributions.

INTRODUCTION

THE reaction $N^{14}(N^{14},N^{13})N^{15}$ has been investigated previously by Reynolds and Zucker.[1] Excitation functions were obtained using thick AgCN targets and, with the use of nitrogen gas targets, a rough angular distribution of N^{13} particles was determined. Reynolds and Zucker interpreted the reaction as proceeding by means of a neutron transferring from one N^{14} nucleus to the other. The present work was undertaken to improve and extend the N^{13} angular distribution data by using thin targets of a solid nitrogen-bearing compound.

At the outset, it was noted that the reaction was quite distinctive in that: (1) N^{13} excited states are unstable with respect to proton emission to C^{12}, so that N^{13} nuclei detected are necessarily found in their ground states, and (2) the first excited state in N^{15} occurs at 5.28 Mev. Thus, N^{13} nuclei resulting from transfers to the N^{15} ground state (ground-state transfers) are approximately 5 Mev more energetic than those leaving N^{15} recoils in excited states (excited-state transfers). The large energy gap made it possible to distinguish the two sets of N^{13} particles.

An earlier brief communication[2] dealt with the change in the relative amounts of ground- and excited-state transfers at various angles as the incident N^{14} energy was varied. The data reported at that time indicated that with decreasing bombarding energy, excited-state transfers become more numerous than ground-state transfers. The observation is confirmed by the present experimental information obtained with improved resolution at the larger angles.

EXPERIMENTAL METHOD

The N^{14} beam consisted of N^{3+} ions accelerated to about 28 Mev in the Oak Ridge 63-in. cyclotron. The experimental arrangement is shown in Fig. 1. A circular

* Operated by the U. S. Atomic Energy Commission by Union Carbide Corporation.
[1] H. L. Reynolds and A. Zucker, Phys. Rev. **101**, 166 (1956).
[2] K. S. Toth, Phys. Rev. **121**, 1190 (1961).

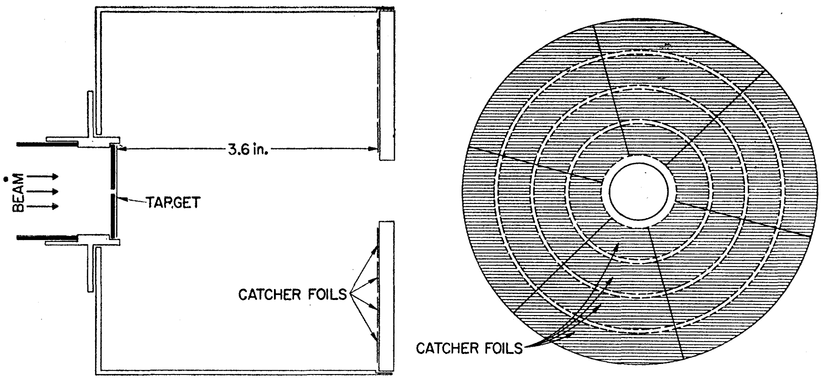

FIG. 1. Experimental arrangement.

chimney rests on a support which in turn is placed on the vertical beam pipe. The collimator is $\frac{1}{8}$ in. in diameter. Reaction products are stopped in concentric circular strips of aluminum foil attached to a circular metal disk placed on top of the chimney. The beam, after traversing the target, passes through the hole in the disk, and the beam intensity is measured in a Faraday cup. The distance between the target and the metal disk, together with the inside and outside radii of a given aluminum strip, gives the angles encompassed by that particular strip.

The target material was a nitrogen-bearing resin Cymel 248-8. This is a butylated melamine-formaldehyde condensate supplied as 55% solids in a mixture of butanol and xylene.[3] Its approximate composition by weight is: nitrogen 24%, carbon 52%, oxygen 16%, and hydrogen 8%. However, for a dry film of the resin this composition changes, since water and some butanol are released during drying. Attempts to make self-supporting Cymel films that could withstand the beam in the target assembly were unsuccessful. Bombardments described in this work were made with Cymel films on two types of backing: (a) 150 $\mu g/cm^2$ aluminum foil, and (b) 50–100 $\mu g/cm^2$ carbon films.

Targets were prepared by allowing a drop of the resin to spread on a water surface. The film was then picked off the water onto a metal frame already supporting either one of the two backings. The arrangement was then left to dry. Target thicknesses were found by measuring the energy of the N^{14} beam, then inserting the targets and determining the energy loss suffered by the beam in traversing the targets. The N^{14} beam energy was measured to be 28.0 Mev. The average loss suffered by the beam in Cymel films was $\sim$1.5 Mev. It was discovered that with each successive bombardment the targets lost some of their nitrogen. Therefore, to keep the N^{13} yield at a reasonable level, new spots on the targets were exposed to the beam after 3 or 4 bombardments; subsequently new targets were prepared.

From kinematics, the N^{13} energies at various angles were calculated for transfers leaving N^{15} recoils in their (1) ground state and (2) first excited state. Then, to determine the angular distribution for N^{13} particles resulting from ground-state transfers, aluminum absorber foils of sufficient thickness to stop undesired N^{13} particles were placed in front of the catcher foils. Absorbers also stopped most other reaction products which, because of their higher atomic numbers have shorter ranges than nitrogen particles. From the range curves of Northcliffe for nitrogen ions in aluminum[4] the difference between the ranges of N^{13} and N^{14} ions was found to be negligible. An experimental range vs energy curve for N^{14} in aluminum[5] was then utilized for the transformation of the quantity of absorber to the corresponding N^{13} energy.

Figure 2 illustrates how the selection of N^{13} particles was accomplished. N^{13} energies at all angles were calculated for N^{14} incident beams of varying energies and plotted as a function of laboratory angle. The top three curves in Fig. 3 are for ground-state transfers with a Q of 0.29 Mev. The three cases relate to N^{14} energies after the beam penetrates (1) the aluminum backing (27.1 Mev); (2) the backing plus a 1.1-Mev thick target (26.0 Mev); and (3) the backing and a 2.5-Mev thick target (24.6 Mev). The lowest curve is for 27.1 Mev N^{14} ions, but here the transfer has occurred to the first excited state in N^{15} and Q for the reaction is -5.00 Mev. Vertical, light, dashed lines represent the angular acceptance of the catcher foils. Short, heavy, dashed curves going across represent the absorber thickness (in Mev) used to stop the undesired N^{13} particles and yet allow the wanted ground-state transfer N^{13} nuclei through, even for a 2.5-Mev thick target. A product nucleus entering the absorber at an angle traverses through a greater thickness than if the nucleus had entered normal to the absorber foil; this is why these dashed curves are shown to rise with angle.

To determine the relative amounts of ground- and excited-state transfers, range curves were obtained by

[3] The Cymel resin was kindly supplied to us by J. K. Magrane, Manager, Plastics and Resin Section, Polymer Research Department, Stamford Laboratories, American Cyanamid Company, Stamford, Connecticut.

[4] L. C. Northcliffe, Yale University, privately distributed curves.

[5] W. H. Webb, H. L. Reynolds, and A. Zucker, Phys. Rev. **102**, 749 (1956).

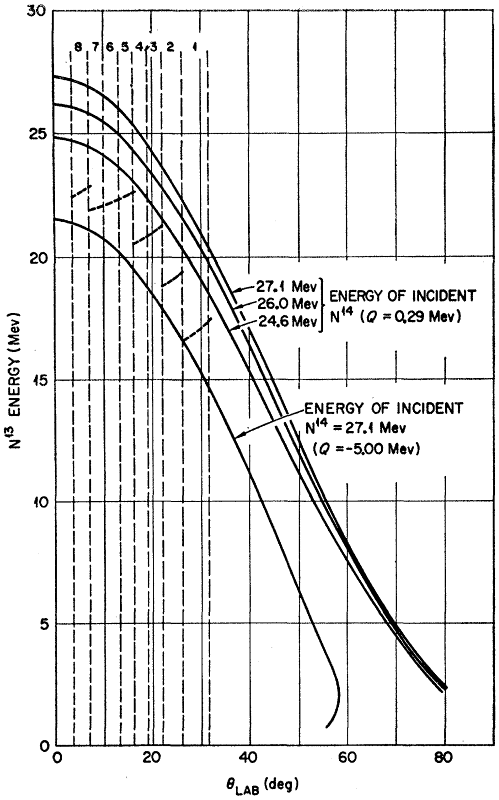

FIG. 2. Nitrogen-13 energies at all angles calculated from kinematics for the reaction $N^{14}(N^{14},N^{13})N^{15}$, for various incident energies. Vertical dashed lines indicate the angular spread encompassed by each catcher foil. The short, heavy, dashed curves represent in Mev the effective amount of absorber placed before each catcher, as a function of N^{13} angle.

varying the amount of absorber placed before the catcher foils.

After 20-min bombardments the aluminum foils were detached from the disk holder. Catchers were separated from absorber foils, and the former were then folded and counted directly under shielded calibrated Geiger counters. The catchers were thin enough so that absorption of β particles in the aluminum was not a problem. The amount of N^{13} present in each catcher was found by resolving the 10-min N^{13} half-life from the gross decay curve. Two half-lives were ordinarily present in the decay curves—the 10-min N^{13} and 2-hr F^{18}. Ten-minute activity (N^{13} and K^{38}) contributed by the aluminum backing in each catcher was determined by bombarding the backing with no Cymel on it. Where significant, this contribution was subtracted from the total 10-min activity. Bombardments of carbon foils resulted in insignificant amounts of 10-min activity at all angles, absorber thicknesses, and bombarding energies. This shows that N^{13} contribution from carbon in the target and the backing was negligible. N^{13} contribution due to transfers on O^{16} was not determined experimentally but assumed to be negligible since the transfer cross section[6] on O^{16} is smaller than that on C^{12}.

EXPERIMENTAL RESULTS

Figure 3 shows angular distributions for N^{13} nuclei resulting from ground-state transfers and taken at incident energies of 27.1 and 23.1 Mev. Aluminum-backed targets were utilized. The N^{14} beam was allowed to strike the backing first. The ordinate is in arbitrary units of the differential cross section and applies to both distributions. The 27.1-Mev data represent an average of eight runs; six runs are averaged for the 23.1-Mev distribution. For a given bombarding energy the runs are normalized to one another by assuming the peak activity (25.5°–31°) equal for all runs. The two distributions were interrelated by bombarding the same targets at both energies.

The data displayed in Fig. 3 are in agreement with the proposed neutron transfer mechanism for the reaction $N^{14}(N^{14},N^{13})N^{15}$. The differential cross sections at both energies decrease at small angles where collisions are distant. They also decrease at large angles (close collisions) where compound nucleus formation would be expected to compete.

Errors in the angular distribution shown in Fig. 3 may be divided into two groups: (1) those contributing to the angular spread and (2) those producing uncertainties in the ordinate scale. The main contribution to the

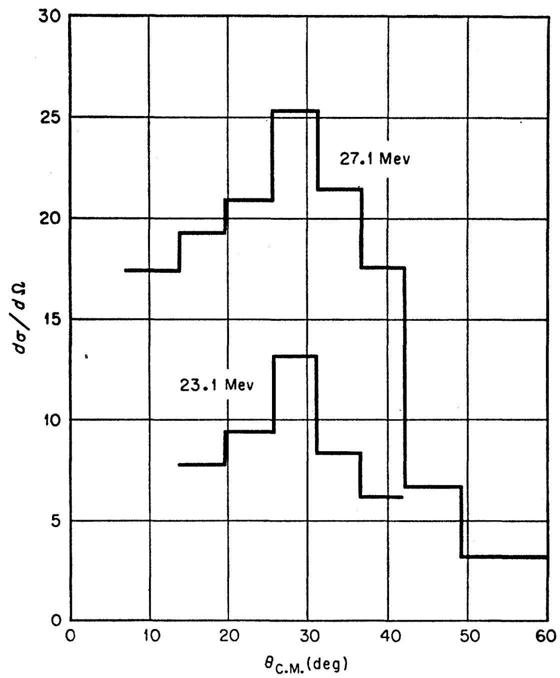

FIG. 3. Angular distributions of N^{13} due to ground-state transfers and obtained at incident energies of 27.1 and 23.1 Mev.

[6] M. L. Halbert, T. H. Handley, J. J. Pinajian, W. H. Webb, and A. Zucker, Phys. Rev. 106, 251 (1957).

angular spread comes from the finite size of the collimator. The spreads calculated for angles (in the laboratory system) from 12° to 32° vary from ±57 to ±43 min. The spread introduced by multiple scattering in the target was estimated to be about ±25 min, substantially less than that due to the finite size of the collimator. Two main errors contribute to the ordinate scale uncertainty. One is the Geiger counter efficiency which is known to about 10%. This systematic inaccuracy was averaged out by distributing the foils differently among the counters from run to run. The second important uncertainty arises when determining the amount of 10-min activity present in each decay curve. This uncertainty was appreciable only when the counting rate was low and was particularly important in some decay curves obtained at 23.1 Mev. In extreme cases the uncertainty was ~30%. It was hoped this inaccuracy could be at least partially eliminated by averaging the six runs taken at 23.1 Mev.

From Fig. 3 the indication is that the ground-state transfer cross section decreases (by a factor ~2.3) as the bombarding energy is lowered from 27.1 Mev to 23.1 Mev. Reynolds and Zucker[1] have shown that the total cross section for the reaction remains fairly constant for incident energies between 19 and 27 Mev. To reconcile the two sets of data it was postulated that as the energy is lowered, transfers to excited states become more prevalent. To test this possibility the activity from 16° to 32° (lab) was investigated as a function of the amount of absorber placed before each catcher at three bombarding energies. The catchers were always thick enough to stop all N^{13} particles sufficiently energetic to penetrate through the absorbers.

Figures 4–6 show the range curves obtained at 28.0, 24.0, and 19.8 Mev incident energy. Carbon-backed Cymel targets were used in these runs. The beam struck the Cymel film first; therefore, the maximum N^{14} energy is taken to be 28.0 Mev. Any curve may be directly compared with any other because ordinates for Figs. 4–6 are in arbitrary units of N^{13} activity and normalized to one another for all angles and all incident N^{14} energies. The abscissas express the quantity of absorber in terms of the corresponding N^{13} energy. The curves clearly show that as the energy is lowered to 24.0 Mev fewer N^{13} particles due to ground-state transfers are observed. At 19.8 Mev no long-range N^{13} activity is seen in the angular increment examined.

Four arrows in two sets of two are shown for each curve in Figs. 4–6. The two arrows at the higher energy indicate N^{13} energies calculated from kinematics for ground-state transfers for the two extreme angles encompassed by the particular catcher. The lower energy set indicates the two energies for transfers proceeding to the first excited state in N^{15}. For each curve the quantities of aluminum absorber have been transformed to the corresponding N^{13} energy by utilizing the angle midway between the two extreme angles for the transformation. The experimental curves drop off at approximately the energies predicted from kinematics for ground- and first excited-state transfers. The indication, then, is that the steps in the curves represent quite accurately the ranges of N^{13} nuclei due to first excited- and ground-state transfers. The range curves were obtained so that transfers to all excited states in N^{15} up to about 8 or 9 Mev would be included. Figures 4–6 show the curves to level off once the first two excited states (5.28 and 5.31 Mev) are included; apparently only these two excited states (or one of them) contribute importantly to the transfer reaction.

Table I summarizes the activity, in arbitrary units,

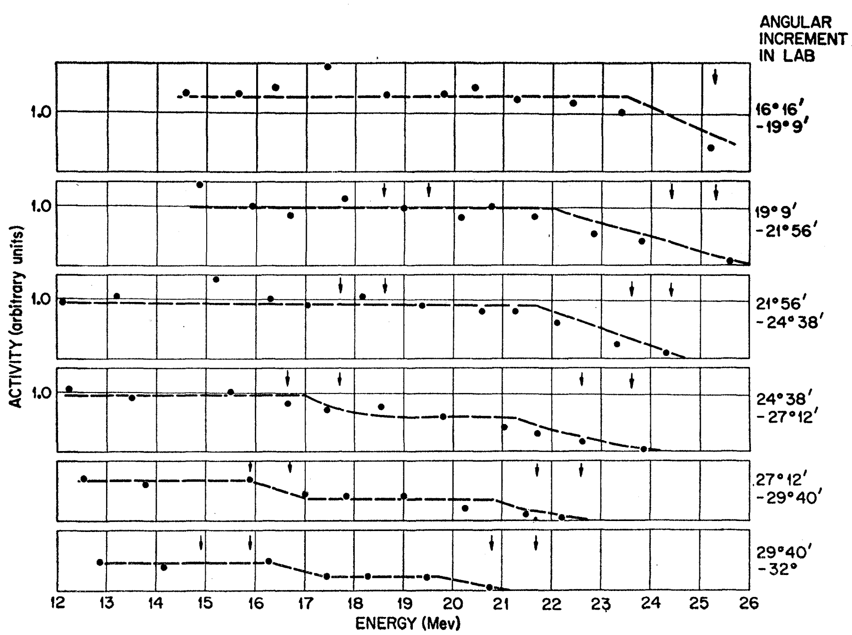

FIG. 4. N^{13} range curves obtained at an incident energy of 28.0 Mev. Ordinate scales express N^{13} activity in arbitrary units. These units apply to all range curves including those obtained at incident energies of 24.0 and 19.8 Mev (see Figs. 5 and 6). The quantity of absorber (abscissa) has been converted to the corresponding N^{13} energy in Mev.

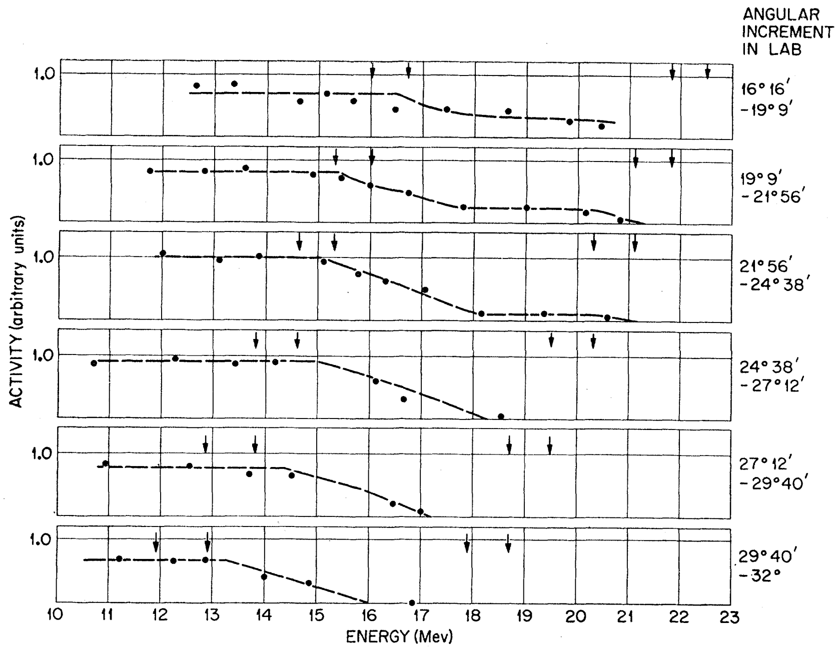

FIG. 5. N^{13} range curves obtained at an incident energy of 24.0 Mev. Ordinate scales express N^{13} activity in arbitrary units. These units apply to all range curves (see Figs. 4 and 6). The quantity of absorber (abscissa) has been converted to the corresponding N^{13} energy in Mev.

seen for all the catchers at the three bombarding energies. For the angular increment studied, the total activity (proportional to the cross section) decreases little as the incident N^{14} energy is lowered from 28.0 to 24.0 to 19.8 Mev. This agrees with the data of Reynolds and Zucker.[1]

By assuming that the total activity in each catcher minus the activity due to the long-range N^{13} nuclei represents transfers to the first and/or second excited states in N^{15}, angular distributions for these transfers have been derived from the 24.0- and 19.8-Mev data. These are shown in Fig. 7. One must recall that the data in Fig. 3 were obtained using aluminum-backed targets (maximum incident energy of 27.1 Mev) while data in Figs. 4–6 were taken with carbon-backed targets (maximum incident energy of 28.0 Mev). By assuming that one specific catcher (13°–16°, lab), for the same thickness of absorber placed before it, had an equal amount of N^{13} activity at both 27.1 and 28.0 Mev, the results obtained with the aluminum- and carbon-backed targets were interrelated. The ordinate in Fig. 7 is therefore in the same arbitrary units of $d\sigma/d\Omega$ that were used in Fig. 3. Only a partial angular distribution for ground state N^{13} nuclei at 24.0 Mev could be constructed from Fig. 5. This incomplete distribution is shown in Fig. 7, together with the 23.1-Mev ground-state distribution

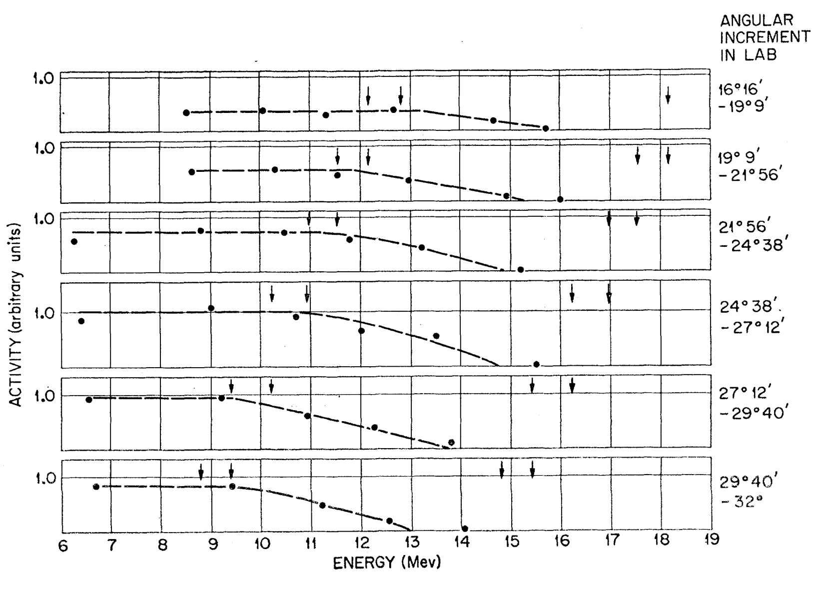

FIG. 6. N^{13} range curves obtained at an incident energy of 19.8 Mev. Ordinate scales express N^{13} activity in arbitrary units. These units apply to all range curves (see Figs. 4 and 5). The quantity of absorber (abscissa) has been converted to the corresponding N^{13} energy in Mev.

TABLE I. N^{13} activity seen at various angular increments[a] and expressed in the same arbitrary units used in the range curves shown in Figs. 4–6.

Incident N^{14} energy (Mev)	16° 16′ to 19° 9′	19° 9′ to 21° 56′	21° 56′ to 24° 38′	24° 38′ to 27° 12′	27° 12′ to 29° 40′	29° 40′ to 32°	Total (16° 16′–32°)
28.0	1.20	1.00	0.90	0.95	0.65	0.55	5.25
24.0	0.70	0.80	1.00	0.90	0.80	0.65	4.85
19.8	0.35	0.60	0.70	1.0	1.0	0.85	4.50

[a] All angles are in the laboratory system.

taken from Fig. 3. The agreement at overlapping angles between the two sets of data is good.

It is clear from Fig. 7 that N^{13} particles from excited-state transfers peak at larger angles than N^{13} nuclei resulting from ground state transfers. There is also an indication that the excited-state transfer peak shifts to larger angles as the bombarding energy is lowered. There seems to be no such shift for the ground-state transfer data shown in Fig. 3.

DISCUSSION

By the method initiated by McIntyre *et al.*[7] the information displayed in Figs. 3 and 7 has been replotted in Fig. 8 as $d\sigma/dR_{\min}$ vs $R_{\min}$. Here, $R_{\min}$ is the minimum distance of approach along a Rutherford orbit, i.e.,

$$R_{\min}=\frac{Z_1Z_2e^2}{2E_{\text{c.m.}}}[1+\csc(\theta/2)]. \tag{1}$$

Through Eq. (1) it is found that $d\sigma/dR_{\min}$ is proportional to $(d\sigma/d\Omega)\sin^3(\theta/2)$. In turn, $R_{\min}$ can be related to the parameter r_0 by

$$R_{\min}=r_0(A_1^{\frac{1}{3}}+A_2^{\frac{1}{3}}). \tag{2}$$

The data are normalized to the 27.1-Mev ground-state transfer N^{13} distribution (points "A" in Fig. 8). Sufficient data to see an actual maximum are available for only this distribution. It peaks at an $R_{\min}$ of 10.5 f, and a resultant $r_0=2.2$ f. The large r_0 would tend to indicate that ground-state transfers occur while the interacting nuclei are widely separated. While excited-state data (points "C" and "D") are insufficient to show a maximum, it is clear that the two distributions would peak at a smaller $R_{\min}$, ~8 f, corresponding to an r_0 of ~1.65 f. It is doubtful that a meaningful correlation can be made between the angle at which the differential cross section peaks and the distance of closest approach for excited-state transfers where Q for the reaction is −5.00 Mev compared to an $E_{\text{c.m.}}$ of 12.0 Mev. One would expect that N^{13} particles resulting from transfers in which the Q was −5.00 Mev would be deflected more than those from ground-state transfers ($Q=0.29$ Mev). They would therefore be detected at angles larger than those due to ground-state transfers. However, this would not necessarily mean that the excited transfers took place at a smaller $R_{\min}$.

The experimental information can be compared with the tunneling theory of Breit and Ebel[8] who derive the angular dependence of $d\sigma/d\Omega$. McIntyre *et al.*[7] show that after $d\sigma/d\Omega$ is transformed to $d\sigma/dR_{\min}$, the angular dependence of $d\sigma/dR_{\min}$ is found to be proportional to

$$\exp(-2\alpha R_{\min}), \tag{3}$$

where

$$\alpha=[(2M/\hbar^2)E_s]^{\frac{1}{2}}, \tag{4}$$

M being the mass of the transferred nucleon and E_s the separation energy of the nucleon from its parent nucleus. Tunneling theory is not expected to agree with data at small $R_{\min}$, where trajectories penetrate the absorption radius and compound nucleus formation would be expected to come to the fore. In an effort to fit the data at large $R_{\min}$, two lines with an identical slope derived from Eq. (3) have been drawn in Fig. 8, one for ground-state and the other for excited-state distributions. The fit is far from perfect for either of the two sets of data;

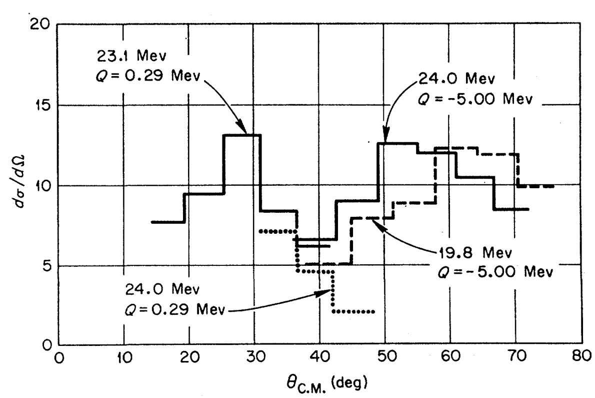

FIG. 7. Angular distributions of N^{13} due to transfers to the first and/or second excited state in N^{15} and obtained at incident energies of 24.0 and 19.8 Mev. The ordinate scale is in the same arbitrary units of differential cross section that were used in Fig. 3. The distribution of N^{13} due to ground-state transfers at 23.1 Mev taken from Fig. 3 is included for comparison. A partial angular distribution of N^{13} due to ground-state transfers at 24.0 Mev incident energy is also included.

[7] J. A. McIntyre, T. L. Watts, and F. C. Jobes, Phys. Rev. **119**, 1331 (1960).

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

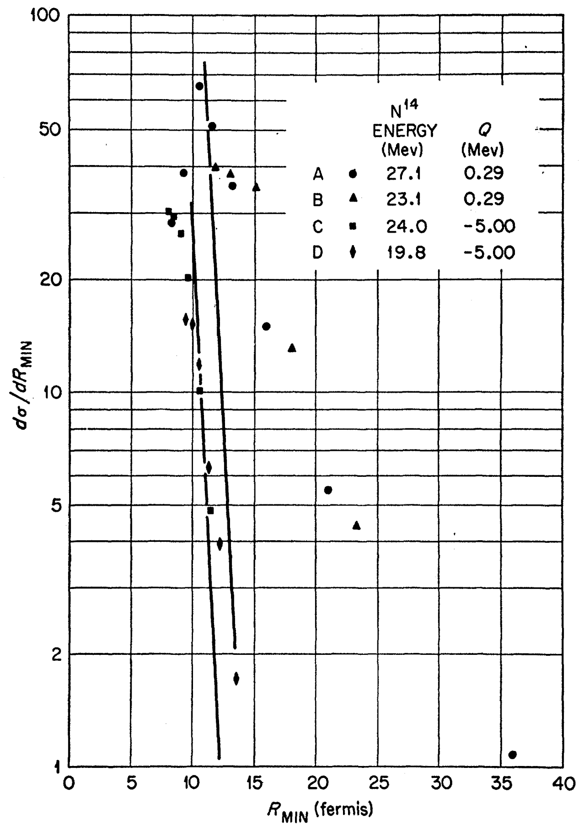

FIG. 8. Angular distribution data of Figs. 3 and 7 plotted as $d\sigma/dR_{\min}$ vs $R_{\min}$. Two lines with an identical slope calculated from the tunneling theory of Breit and Ebel as given in Eq. (3) are also drawn. One is drawn as a best fit to the excited-state transfer data (points C and D), the other as a best fit to the ground-state transfer results (points A and B).

but it is evident that the fit is better for the excited-state distributions.

A modification of the theory has been formulated by Breit,[9] in which Eq. (3) is changed to

$$\exp(-\alpha R_{\min}-\bar{\alpha}\bar{R}_{\min}), \tag{5}$$

the unbarred and barred quantities representing the initial and final states of the system, respectively.

$$\bar{\alpha}=[(2M/\hbar^2)\bar{E}_s]^{\frac{1}{2}}, \tag{6}$$

where

$$\bar{E}_s=E_s+Q. \tag{7}$$

$\bar{R}_{\min}$ differs from $R_{\min}$ in that it is calculated from Eq. (1) using $\bar{E}_{\text{c.m.}}$, where

$$\bar{E}_{\text{c.m.}}=E_{\text{c.m.}}+Q. \tag{8}$$

For the reaction studied here, the slopes of the lines derived from Eq. (5) were compared to that derived from Eq. (3). It was found that (a) for ground state transfers at both bombarding energies the slopes were essentially unchanged from the Eq. (3) slope, and (b) for excited state transfers the Eq. (5) lines were slightly steeper than the Eq. (3) line and thus provided a poorer fit to the experimental data. In the case of excited-state transfers the differences between the slopes derived from Eq. (5) and that derived from Eq. (3) are on the order of 1 or 2%, and would be almost imperceptible in Fig. 8. It should also be pointed out that virtual Coulomb excitation as a possible mechanism[9] has not been considered, though it may be important at low bombarding energies.

We should like to compare our experimental results with those obtained by McIntyre *et al.*[7] for the neutron transfer reaction $Au^{197}(N^{14},N^{13})Au^{198}$. They were unable to distinguish between transfers leading to discrete states in Au^{198}. However, from their N^{13} range curves obtained at 81 and 119 Mev in c.m. there is an indication of a shift in the range distribution, as the energy is lowered, toward less energetic N^{13} particles, i.e., toward more excited-state transfers. This shift seems to be reflected in their N^{13} angular distributions plotted as $d\sigma/dR_{\min}$ vs $R_{\min}$. At bombarding energies much higher than the Coulomb barrier their distributions show substantial cross sections at large $R_{\min}$. As the bombarding energy is lowered these cross sections at large $R_{\min}$ decrease. Our data in Fig. 8 show a similar variation with bombarding energy. The differential cross sections at large $R_{\min}$ are due to ground-state transfers and the cross section for these transfers decreases as the incident N^{14} energy is lowered.

ACKNOWLEDGMENTS

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[9] G. Breit in *Proceedings of the Second Conference on Reactions Between Complex Nuclei, May 2–4, 1960, Gatlinburg, Tennessee* (John Wiley & Sons, Inc., New York, 1960), p. 1.