Angular Distribution and Ranges of N^{13} Particles Resulting from 27.5-Mev N^{14} Ions on Mg^{24}

K. S. TOTH
Oak Ridge National Laboratory, Oak Ridge, Tennessee*
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The angular distribution and ranges are reported for N^{13} nuclei resulting from the transfer reaction $Mg^{24}(N^{14},N^{13})Mg^{25}$ ($Q=-3.22$ Mev) at an incident N^{14} energy of 27.5 Mev. The data are compared to those reported previously for the reaction $Mg^{25}(N^{14},N^{13})Mg^{26}$ ($Q=0.57$ Mev) to study the effect of Q. It is found that while the angular distributions are similar in shape, Mg^{26} states up to 7-Mev excitation contribute significantly to the reaction $Mg^{25}(N^{14},N^{13})Mg^{26}$ in contrast to the presented Mg^{24} data which show no Mg^{25} states above $\sim$5 Mev contributing to the transfer process. The N^{13} ranges when expressed as a function of Q indicate the bulk of N^{13} particles lying between similar Q values for both reactions. Excited-state transfers predominate in the two magnesium reactions in contrast to results reported at the same N^{14} incident energy for B^{10} and N^{14} targets in which ground-state transfers accounted for approximately half of the total cross sections. The angular distributions are replotted as $d\sigma/dR_{min}$ vs R_{min} and r_0's calculated for the peak values of R_{min}; the r_0's are 1.6 f and 1.55 f for Mg^{24} and Mg^{25} targets, respectively. The magnesium data are compared to the tunneling theory for transfer reactions and fair agreement is found.

INTRODUCTION

THE investigation reported here is part of the research at the Oak Ridge 63-inch cyclotron in the field of single-nucleon transfer reactions. The effect of E^*, where $E^*=[E_{c.m.}-E_{barrier}]+Q$, on transfer-reaction cross sections was noted elsewhere[1]; when plotted as a function of E^*, these cross sections, with a few exceptions, lie on a "universal" curve. Recent work on angular distributions of transfers leading to discrete final states[2,3] has shown that: (1) transfers to excited states are detected at angles larger than those at which ground-state transfers are detected, and (2) when the bombarding energy is lowered the cross section for ground-state transfers decreases while that for excited states increases.

The present work was undertaken to determine what effects the components of E^* have on the angular distribution of transfer products and on the population of final states of the residual nuclei. The results of the investigated reaction, $Mg^{24}(N^{14},N^{13})Mg^{25}$ ($Q=-3.22$ Mev) will be compared with those reported[4] for the reaction $Mg^{25}(N^{14},N^{13})Mg^{26}$ where $Q=0.57$ Mev. Since $[E_{c.m.}-E_{barrier}]$ is essentially the same for both reactions, such a comparison should indicate something about the effect of Q, and perhaps the effect of nuclear structure, because Mg^{25} and Mg^{26} differ in their level spins and structures. The data obtained from the two magnesium isotopes will then be compared with results[3,5] from the interaction of 27.5-Mev N^{14} particles on targets of lower atomic number, i.e., N^{14} and B^{10}. Such a comparison should show what effect a substantial difference in the quantity $[E_{c.m.}-E_{barrier}]$ has on transfer reactions.

* Operated for the U. S. Atomic Energy Commission by Union Carbide Corporation.
[1] M. L. Halbert, T. H. Handley, J. J. Pinajian, W. H. Webb, and A. Zucker, Phys. Rev. **106**, 251 (1957).
[2] K. S. Toth, Phys. Rev. **121**, 1190 (1961).
[3] K. S. Toth, Phys. Rev. **123**, 582 (1961).
[4] M. L. Halbert and A. Zucker, Phys. Rev. **108**, 336 (1957).
[5] E. Newman, Phys. Rev. **125**, 600 (1962).

EXPERIMENTAL METHOD

Nitrogen-14 ions were accelerated in the Oak Ridge 63-in. cyclotron to an energy[6] of about 27.5 Mev. The target used was prepared[7] from magnesium enriched in Mg^{24} to 99.7%. The target, including the carbon backing, was weighed and found to be approximately 150 $\mu g/cm^2$, or about 1-Mev thick to the N^{14} beam.

Since the experimental procedure was described earlier,[2,3] it will be dealt with only briefly here. Angular distributions were obtained by stopping the N^{13} particles in circular strips of aluminum foil, each encompassing a known angular increment. These strips were then counted in shielded and calibrated Geiger counters. The amount of N^{13} (10-min half-life) present in each strip was determined from the decay curve. Range curves were obtained by varying the quantity of aluminum absorber placed before the circular catchers. The beam spread, the target thickness, and the angular spread of the various increments account for a total energy spread of $\sim$1.5 Mev. Since the average energy difference between the lower-lying Mg^{25} states is $\sim$0.5 Mev, no attempt was made to distinguish N^{13} particles resulting from transfers to the various Mg^{25} states. Nitrogen-13 excited states are unstable with respect to particle emission and, therefore, detected N^{13} nuclei are necessarily formed in their ground states.

RESULTS

The N^{13} integral range curves obtained at an N^{14} bombarding energy of 27.5 Mev and in the region of 26.5 to 56° in the laboratory system are shown in Fig. 1. The curves represent the amount of N^{13} activity in a particular aluminum catcher plotted as a function of the quantity of aluminum absorber placed between the target and the catcher. The amount of absorber has been converted to the corresponding energy, in Mev, of an

[6] M. L. Halbert and A. Zucker, Phys. Rev. **121**, 236 (1961).
[7] G. R. Hoke and E. Newman, Oak Ridge National Laboratory Report ORNL-3021, (1961).

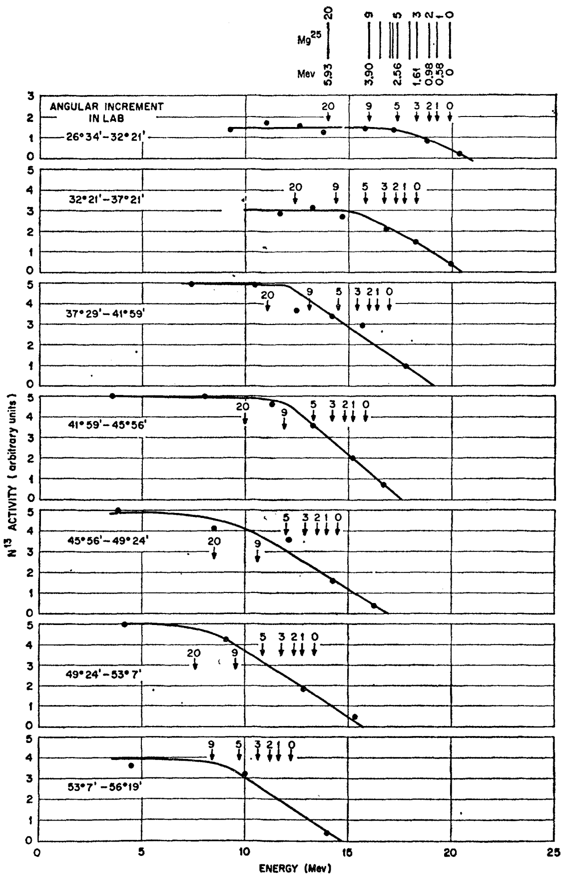

FIG. 1. Nitrogen[13] integral range curves obtained from N^{14} on Mg^{24} at an incident energy of 27.5 Mev. The curves represent the N^{13} activity in arbitrary units (ordinates) plotted as a function of the amount of absorber (abscissa) placed before the catcher foils. The quantity of absorber has been converted to the corresponding N^{13} energy in Mev. Arrows placed above the curves show the average N^{13} energy calculated for transfers leaving the Mg^{25} nuclei in various states. The arrows are accompanied by numbers that identify which Mg^{25} state the N^{13} energy is calculated for. A Mg^{25} level diagram is also shown.

N^{13} particle which would be stopped in that quantity of absorber. The experimental range energy curve of Webb *et al.*[8] for N^{14} particles in aluminum was used for the conversion; advantage was taken of the fact that N^{13} and N^{14} ranges at these energies are essentially identical.[9] Arrows placed over the curves indicate the average N^{13} energies for various final Mg^{25} states in the various angular increments.

The range curves level off after a given excited state in Mg^{25} (depending on the angular increment) has been included, indicating that transfers to higher Mg^{25} states do not occur. The highest contributing state in Mg^{25} seems to be less than $\sim$5 Mev in excitation. From the data shown in Fig. 1, the differential cross section, $d\sigma/d\Omega$, was calculated as a function of $\theta_{c.m.}$, as shown in Fig. 2. Two N^{13} angular distributions are drawn; one assumes that all transfers proceed to the 1.61-Mev state of Mg^{25}, this appears to be a representative state involved in the transfer process; the other, to show an extreme case, assumes that only the 5.93-Mev state is involved. Other Mg^{25} states undoubtedly participate in the transfer reaction; the true distribution is probably somewhere in between the two shown in Fig. 2. It is clear, however, that the two histograms are similar in appearance. The inset in Fig. 2 shows the N^{13} angular distribution obtained[4] for $Mg^{25}(N^{14},N^{13})Mg^{26}$.

The cross section encompassed by the angular acceptance was calculated to be 1.0±0.3 mb. Fig. 2 suggests that only half of the total cross section was included. The total cross section at the full bombarding energy of the cyclotron has been measured[1] to be ≈ 3 mb. The estimated value of 2 mb obtained here is lower, but the discrepancy is probably not real because impurities, particularly carbon and oxygen, are known to be present in the target. The impurities increase the target weight but do not increase the N^{13} yield significantly, since the reported[1] cross sections for N^{13} resulting from 27.5-Mev N^{14} on C^{12} and O^{16} are 0.22 and 0.13 mb, respectively.

DISCUSSION

The N^{13} angular distributions obtained from the two magnesium targets are similar in shape. For a comparable excitation in the residual nucleus the Mg^{25} distribution reaches a maximum at a center-of-mass angle approximately 10° smaller than for the Mg^{24} distribution. Also, Mg^{26} states up to 7-Mev excitation have been found[4] to contribute significantly to the transfer cross section in the $Mg^{25}(N^{14},N^{13})Mg^{26}$ reaction. At approximately the same center-of-mass angle the Mg^{24} results indicate no contribution beyond 4-Mev excitation in Mg^{25}. The N^{13} differential range curves for $Mg^{25}(N^{14},N^{13})Mg^{26}$ were converted to integral range curves and plotted as a function of Q. They are shown in Fig. 3, together with the $Mg^{24}(N^{14},N^{13})Mg^{25}$ curves for approximately the same center-of-mass angles; these curves are also replotted vs Q value. The two sets of curves level off at about the same Q; the bulk of N^{13} nuclei are found to lie between the same values of Q for both reactions. There are more N^{13} particles at less negative Q's for the Mg^{25} data, but this is to be expected because at these Q's there are still more Mg^{26} states to which the neutron may transfer. For the case $Mg^{24}(N^{14},N^{13})Mg^{25}$ no Mg^{25} states exist to contribute transfer reactions at such Q values.

A similar experimental result was recently reported by Watts and McIntyre[10] for the two reactions: $Pb^{207}(N^{14},N^{13})Pb^{208}$, $Q=-3.18$ Mev and $Pb^{208}(N^{14},N^{13})Pb^{209}$, $Q=-6.63$ Mev. Their data show that for the same $E_{c.m.}$ and $\theta_{c.m.}$ the Pb^{208} results

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

[9] L. C. Northcliffe, Yale University (privately distributed curves).

[10] T. L. Watts and J. A. McIntyre, "Proceedings of the Rutherford Jubilee International Conference" (to be published).

(reaction with the lower Q) indicate much more transfer occurring to the Pb^{209} ground and low-lying excited states than for the higher Q reaction involving the Pb^{207} target. Their N^{13} differential ranges peak at about the same Q value and exhibit similar shapes for both reactions. Here again the reaction leading to Pb^{209} (comparable to Mg^{25}) cuts off at a more negative Q due to the unavailability of states beyond this Q value. A possible explanation involving angular momentum arguments was suggested for their results. The transferred neutron carries off ~ 5 units of angular momentum (at $E_{\text{c.m.}}=112$ Mev) and would presumably transfer between states involving an appropriate angular momentum change. Another possible explanation would seem to be simply the difference in level densities between odd and even nuclei, there being more low-lying excited states in an odd nucleus than in an even one. This last explanation is prompted by the fact that in the Mg^{25} leading to Mg^{26} reaction the data indicate transfers occurring to the Mg^{26} ground state. Such a transfer involves a $5/2+$ to $0+$ transition for a neutron carrying off an average of 9/14 units of angular momentum. An $l_{\max}$ of $\sim 9\hbar$ has been calculated from the elastic scattering data[11] of 28.2-Mev N^{14} ions on Mg^{24} using the following relationship: $l(l+1)=2\mu R^2\hbar^{-2}\times[E_{\text{c.m.}}-(E_{\text{barrier}})]$, where R is the sum of the two radii. Also, in the Pb reactions the N^{13} ranges do not peak at the final states for which the angular momentum

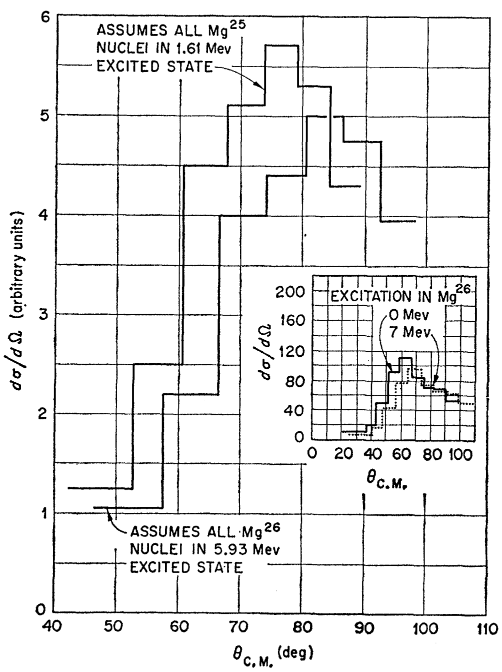

FIG. 2. Angular distribution of N^{13} particles from $Mg^{24}(N^{14},N^{13})Mg^{25}$. The distribution is drawn assuming the residual Mg^{25} nuclei to be in (1) the 3rd excited state (1.61 Mev), and (2) the 20th excited state (5.93 Mev). The inset shows the previously reported N^{13} distribution for $Mg^{25}(N^{14},N^{13})Mg^{26}$.

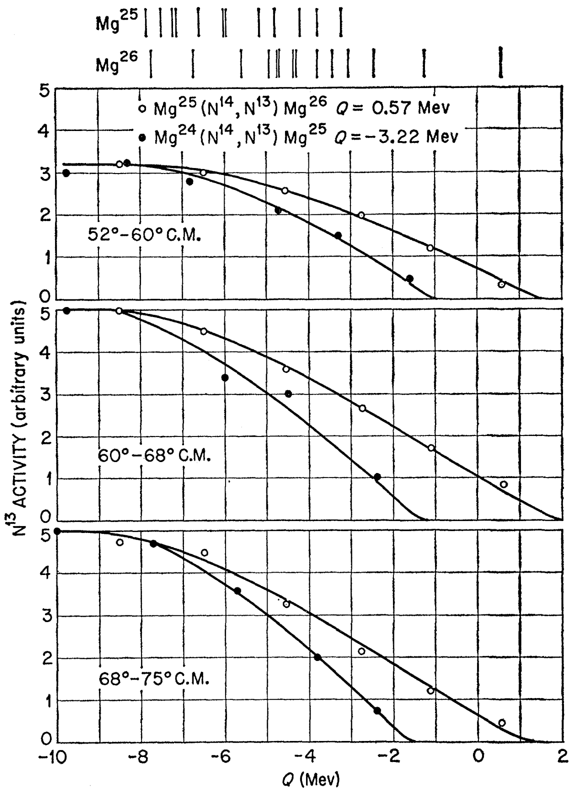

FIG. 3. Integral N^{13} range curves for Mg^{24} and Mg^{25} targets at three angular increments. The curves represent N^{13} activity plotted as a function of excitation in the residual nuclei Mg^{25} and Mg^{26}; this excitation is expressed as Q for the reactions. The two sets of data have been arbitrarily normalized to make the curves level off at the same N^{13} activity. The Mg^{25} and Mg^{26} level schemes are also shown. These are represented in terms of Q values corresponding to neutron transfers to the various levels.

change is most favorable. Perhaps a combination of level density and angular momentum arguments provides the answer. It must be borne in mind that the explanations are all speculative because in neither the lead nor the magnesium data are transfers to individual states distinguished; nothing can be said concerning the exact population of each state.

Angular distributions for transfer reactions to individual final states have been investigated with 27.5-Mev N^{14} ions. Newman[5] studied the reactions $B^{10}(N^{14},O^{15})Be^9$ and $B^{10}(N^{14},C^{13})C^{11}$, while the author[2,3] investigated $N^{14}(N^{14},N^{13})N^{15}$ and recently $B^{10}(N^{14},N^{13})B^{11}$.[12] In all four instances the cross section for the transfers that leave both residual nuclei in their ground states was found to be approximately half of the total cross section. This is in contrast to the magnesium data, taken at the same bombarding energy, where, for both isotopes, transfers to the ground states are unimportant and excited-state transfers predominate. The difference between the two sets of data would appear to reside in the $[E_{\text{c.m.}}-E_{\text{barrier}}]$ term since the Q of 0.57 Mev for

[11] A. Zucker, Bull. Am. Phys. Soc. 6, 285 (1961).

[12] K. S. Toth (unpublished data).

$Mg^{25}(N^{14},N^{13})Mg^{26}$ is comparable with the Q's of the reactions involving targets of B^{10} and N^{14}. These Q's range from 0.29 to 1.14 Mev. The marked lack of ground-state transfers in the magnesium reactions is apparently the same effect as that noted by the author[2,3] in the case of N^{14} on N^{14}. There it was observed that when the bombarding energy was lowered the transfers to the ground state of N^{15} decreased, while those to the excited states increased. As the atomic number of the target is increased E_{barrier} increases more rapidly than $E_{\text{c.m.}}$ if the bombarding energy is kept the same. Thus, increasing the atomic number of the target but keeping the bombarding energy constant, i.e., decreasing the quantity $[E_{\text{c.m.}}-E_{\text{barrier}}]$, has the same effect as that of lowering the bombarding energy. Indeed, it is observed that both changes appear to induce the transfers to proceed preferentially to the excited states of the residual nuclei.

The N^{13} angular distributions for both magnesium reactions are replotted in Fig. 4 as $d\sigma/dR_{\text{min}}$ vs R_{min} as suggested by McIntyre.[13] R_{min} is the distance of closest approach for a classical trajectory, namely:

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

R_{min} is related to the parameter r_0 by the equation: $R_{\text{min}}=r_0(A_1^{\frac{1}{3}}+A_2^{\frac{1}{3}})$. The Mg^{24} data peak at an R_{min} of ≈ 8.5 f, which corresponds to an r_0 of ≈ 1.6 f. The Mg^{25} data yield an r_0 of ≈ 1.55 f. These r_0's are much less than the values of 2.2 f determined[3,5,12] for transfer reactions involving only the ground states of the residual nuclei. The r_0's agree well with that of 1.65 f determined[3] for transfers occurring to the excited states of N^{15}. The r_0's are about the same as the value of 1.54 f found by McIntyre *et al.*[13] in their study of $Au^{197}(N^{14},N^{13})Au^{198}$. There again excited states were predominant in the transfers. It is not clear that a meaningful correlation can be made between the angle at which the differential cross section peaks and the distance of closest approach for transfers where the Q value is quite different from zero. Nitrogen-13 particles resulting from transfers to an excited state would be deflected more than those from transfers to the ground state and, therefore, would be detected at a larger angle. This, however, would not necessarily mean that the transfer to the excited state occurred at a smaller R_{min}.

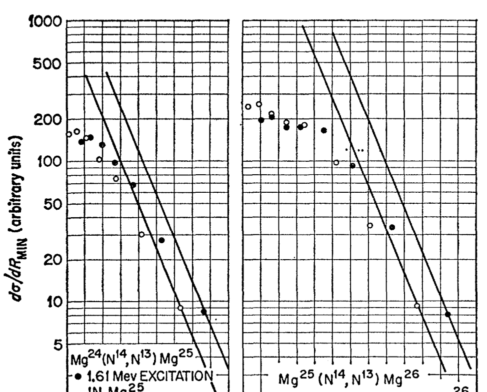

FIG. 4. Angular distribution data of Fig. 2 plotted as $d\sigma dR_{\text{min}}$ vs R_{min}. The lines, normalized to the experimental points, are drawn with slopes calculated from the tunneling theory of Breit.

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

The lines drawn normalized to the experimental points represent the curves for the tunneling process which has been proposed and discussed by Breit as a mechanism for transfer reactions.[14–16] The lines represent the quantity $\exp(-\alpha R_{\text{min}}-\bar{\alpha}\bar{R}_{\text{min}})$ plotted as a function of R_{min}. Here:

$$\alpha=(2ME_s/\hbar^2)^{\frac{1}{2}},\quad\text{and}\quad \bar{\alpha}=(2M\bar{E}_s/\hbar^2)^{\frac{1}{2}}.$$

E_s is the separation energy of the transferred nucleon in the delivering nucleus. $\bar{E}_s=E_s+Q$. M is the mass of the transferred nucleon. $\bar{R}_{\text{min}}$ is calculated in the same manner as R_{min}, except now $[E_{\text{c.m.}}+Q]$ is used in place of $E_{\text{c.m.}}$. The fit of the tunneling curve to the data is not bad, the theoretical slope being somewhat steeper than that of the experimental points. The tunneling theory does not consider the onset of compound nucleus reactions at small distances of approach, and is thus expected to reproduce only the initial rise of the angular distribution at large separation distances. The steepness of the theoretical curve may indicate that compound nucleus reactions begin to play a role at distances larger than expected.

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

[15] G. Breit, *Handbuch der Physik*, edited by S. Flügge (Springer-Verlag, Berlin, 1959), Vol. XLI, Part 1, pp. 367–407.

[16] G. Breit, *Proceedings of the Second Conference on Reactions Between Complex Nuclei* (John Wiley & Sons, Inc., New York, 1960), pp. 1–15.