Neutron Transfer to Excited States in N^{15} in the Reaction $N^{14}(N^{14},N^{13})N^{15}$

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The neutron-transfer reaction, $N^{14}(N^{14},N^{13})N^{15}$, was investigated from 6° to 60° c.m. with 28-Mev N^{14} ions accelerated in the Oak Ridge 63-inch cyclotron. Circular strips of aluminum foil, each encompassing a known angular increment, were used to stop the radioactive N^{13} (10-min). Excited states in N^{13} are unstable with respect to proton emission; the first excited state in N^{15} is 5.28 Mev above ground. Therefore, N^{13} nuclei resulting from transfers to the ground state of N^{15} are at least 5 Mev more energetic than those resulting from transfers to N^{15} excited states. The two groups of N^{13} particles were distinguished by placing suitable absorbers in front of the aluminum catcher foils. It was found that transfers to excited states become more abundant relative to ground state transfers as the incident N^{14} energy is lowered.

THE reaction $N^{14}(N^{14},N^{13})N^{15}$ has been studied previously and interpreted as proceeding by means of a neutron transferring from one N^{14} nucleus to the other.[1] These previous rough measurements are consistent with the present data. Two features in connection with excited states in the product nuclei make the reaction quite distinctive: (1) excited states in N^{13} are unstable with respect to proton emission, so that all N^{13} particles detected are necessarily found in their ground states, and (2) the first excited state in N^{15} occurs at 5.28 Mev above ground. Therefore, N^{13} nuclei resulting from transfers which leave N^{15} nuclei

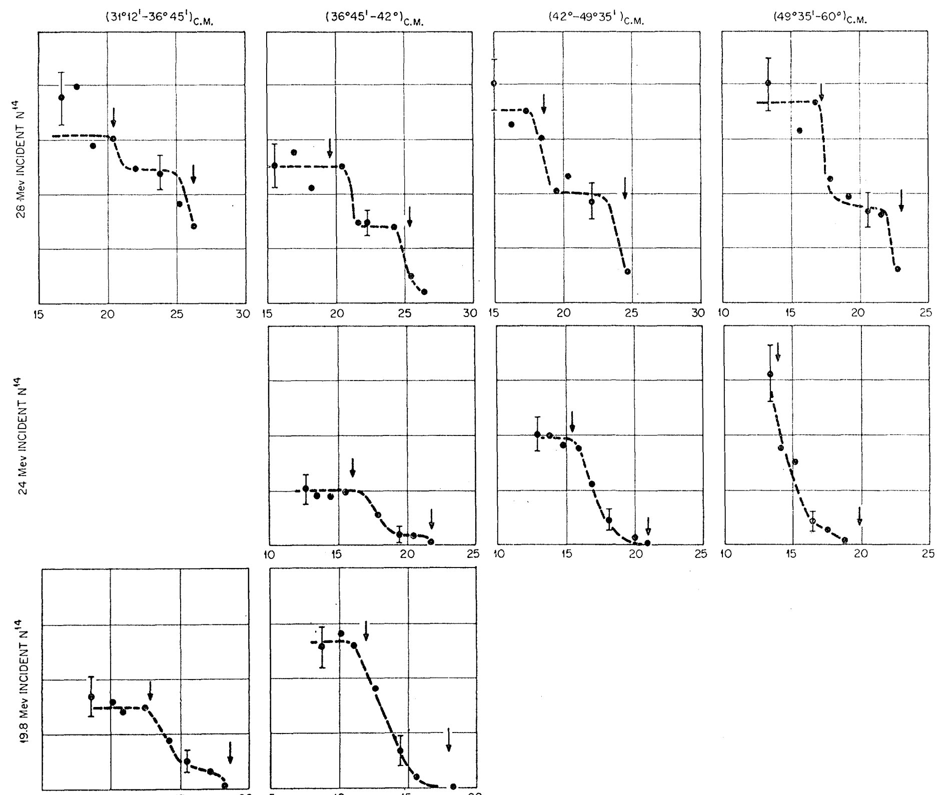

FIG. 1. N^{13} activity at various angular increments plotted as a function of the amount of aluminum absorber placed before the catchers. The quantity of absorber (abscissa) has been converted to the corresponding N^{13} energy in Mev. Ordinate scales are in arbitrary units and represent activity relative to a monitoring catcher whose absorber was kept at a fixed amount for experiments performed at a given N^{14} energy. Thus, curves at one bombarding energy can be compared with one another but no such comparison is possible between curves obtained at different N^{14} incident energies. Maximum N^{13} energies possible for a particular catcher have been calculated from reaction kinematics for N^{15} recoils left in (1) the first excited state, and (2) the ground state. These two energies are indicated by arrows for all the curves in Fig. 1.

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[1] H. L. Reynolds and A. Zucker, Phys. Rev. 101, 166 (1956).

in their ground states (ground state transfers) are on the order of 5 Mev more energetic than those leaving N^{15} recoils in excited states (excited state transfers). The large energy gap thus enables one to distinguish between the two groups of N^{13} particles even using rather crude detection methods.

We have investigated the change in the relative amounts of ground and excited state transfers at various angles as the incident N^{14} energy is varied. No attempt was made to distinguish between transfers occurring to the different N^{15} excited states. Thus a statement in the text concerning excited state transfers refers to transfers taking place to all the excited states in N^{15} up to a certain energy. This energy was between 8 and 9 Mev in all experiments, with one exception where only the first two excited states (5.28 and 5.31 Mev) were included. The range curves shown in Fig. 1 level off once the first two excited states have been included, indicating that apparently only these two excited states contribute importantly to the transfer reaction. Surprisingly, the data show that with decreasing bombarding energy excited state transfers become more numerous than ground state transfers.

The experimental technique will be described briefly. The incident N^{14} particles were accelerated in the Oak Ridge 63-inch cyclotron. The maximum energy is approximately 28 Mev. Targets consisted of a nitrogen-bearing resin called "Cymel" with the following approximate composition: 25% N, 52% C, 16% O, and 7% H, by weight. Product N^{13} nuclei were stopped in concentric circular strips of aluminum foil placed at a known distance away from the target. This distance together with the inner and outer radii of a given strip yielded the angular increment encompassed by that aluminum strip. After bombardment these aluminum catchers were folded and counted directly in shielded calibrated Geiger counters, and the amount of N^{13} present in each catcher found by resolving the 10-min N^{13} half-life from the gross decay curve.

The curves in Fig. 1 display N^{13} activity in a given catcher plotted as a function of the quantity of aluminum absorber placed before the catcher. The quantity of absorber has been transformed in each case to the corresponding N^{13} energy. An experimental range vs energy curve for N^{14} in aluminum was utilized for the transformation.[2] From the curves of Northcliffe for nitrogen ion ranges in aluminum[3] it was determined that the difference between N^{13} and N^{14} ion ranges was negligible.

Two conclusions may be readily drawn from the curves shown in Fig. 1: (1) Excited state transfers are detected at angles larger than those at which ground state transfers appear for a particular bombarding energy; and (2) they become more prevalent relative to ground state transfers as the incident N^{14} energy is lowered. Arrows in Fig. 1 indicate the maximum N^{13} energy possible for a given angular increment for N^{15} recoils left in the ground and first excited states as calculated from reaction kinematics. The experimental curves drop off at approximately the correct maximum energies. The indication is then that the falloffs in the curves are not accidental but represent quite accurately the ranges of N^{13} nuclei due to excited and ground state transfers.

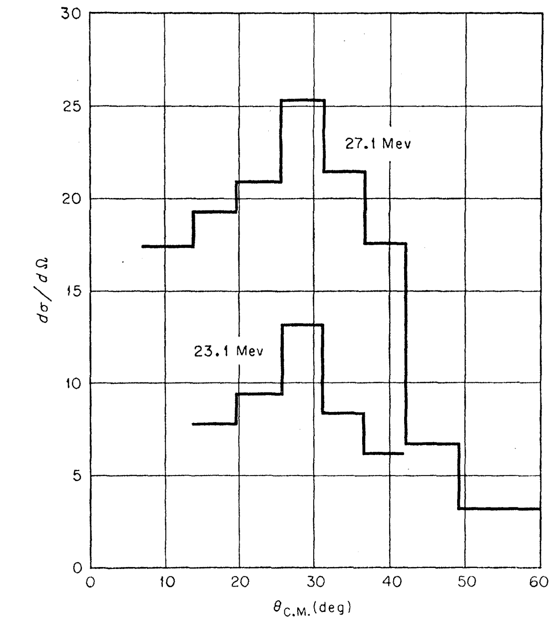

FIG. 2. Angular distributions of N^{13} particles resulting from ground state transfers and obtained at 27.1- and 23.1-Mev bombarding energies. The ordinate is in arbitrary units of the differential cross section and applies to the distributions at both energies. The distribution at 27.1 Mev is an average of 8 runs, while the one at 23.1 Mev is an average of 6 runs. The runs for a given bombarding energy are normalized to one another by arbitrarily assuming the peak activity (25.5°–31°) equal for all such runs. The two distributions were related to one another by bombarding the same target at both energies.

Another piece of evidence for the increased importance of excited state transfers at lower energies is indicated in Fig. 2. The figure shows the angular distribution of N^{13} due to ground state transfers at incident N^{14} energies of 27.1 and 23.1 Mev. Reynolds and Zucker have shown that the total cross section for the reaction $N^{14}(N^{14},N^{13})N^{15}$ remains fairly constant for bombarding energies between 26 and 19 Mev.[1] The large decrease in the amount of ground state transfers in going from 27.1 and 23.1 Mev must therefore mean that transfers to excited states contribute more at the lower energy.

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 is negligible. The N^{13} contribution due to transfers on O^{16} was not determined experimentally. It was assumed to be negli-

[2] W. H. Webb, H. L. Reynolds, and A. Zucker, Phys. Rev. **102**, 749 (1956).
[3] L. C. Northcliffe, Phys. Rev. **120**, 1744 (1960).

gible since the total transfer cross section for the O^{16} reaction is smaller than that for C^{12}.[4]

The expectation would certainly be that at higher bombarding energies transfers to excited states would be more probable than at lower incident energies. The data point to the reverse conclusion. We offer no explanation at the present time.

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

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Measurement of Deuteron Polarization Produced by d-α Scattering at 1.07 Mev

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Elastic scattering from He^4 gas in the energy region of the 1.07-Mev resonance has been used to polarize deuterons. After scattering through 30° in the lab by the polarizer, the polarization of the deuteron beam has been analyzed by the reaction $He^3(d,p)He^4$ near 400 kev. This was accomplished by observing protons at 0° and 90°, and measuring the dependence of the counting rate ratio on the deuteron polarization. $He^3(d,p)He^4$ is well described in this energy region by a single-level Breit-Wigner formula, and therefore has a predictable sensitivity to deuteron polarization. The experimental results are consistent with the magnitude of the polarization component $\langle T_{20}\rangle$ calculated from the $d-\alpha$ phase-shift analysis.

INTRODUCTION

SEVERAL authors have suggested that deuterons elastically scattered from He^4 nuclei should be polarized, both at energies near the 1.07-Mev 3^+ resonance,[1,2] and at higher energies.[3,4] The phase shifts used to make the low-energy polarization predictions were obtained from experimental backward hemisphere differential cross-section measurements.[5] Figure 1, reproduced here for convenience, shows the results obtained in reference 1 for the expected differential cross section and deuteron polarization components at a deuteron scattering angle of 45° in the center-of-mass system, or 30° in the lab system. The "vector" polarization $i\langle T_{11}\rangle$ has been observed through the analyzing reaction $Li^6(d,\alpha)He^4$, and found to have an energy dependence consistent with Fig. 1.[6] The magnitude of $i\langle T_{11}\rangle$ has not been verified because no calibrated analyzer has been available. It was first pointed out by Galonsky *et al.*,[7] however, that the reaction $He^3(d,p)He^4$ should serve as a calibrated analyzer for the components $\langle T_{20}\rangle$, $\langle T_{21}\rangle$, and $\langle T_{22}\rangle$, because a broad single-level resonance dominates the cross section near 400 kev. In this experiment we use the He^3 reaction to check the magnitude and energy dependence of $\langle T_{20}\rangle$.

The quantum numbers for the $He^3(d,p)He^4$ resonance near 400 kev are ${}^4S_{3/2}\rightarrow{}^2D_{3/2}$, giving an isotropic unpolarized cross section.[8] The angular distribution of protons in the center-of-mass system for incident polarized deuterons then follows from the general formula of Simon,[9] and is

$$d\sigma/d\Omega=\tfrac{1}{6}\lambda\!\!\!^{-2}|S|^2\{1-\tfrac{1}{4}\sqrt{2}\langle T_{20}\rangle'(3\cos^2\theta-1) -\sqrt{3}\langle T_{21}\rangle'\sin\theta\cos\theta\cos\phi -\tfrac{1}{2}\sqrt{3}\langle T_{22}\rangle'\sin^2\theta\cos2\phi\},\quad(1)$$

where S is a single-level resonance matrix element.[10] The primed polarization quantities are linear combinations of the first reaction components shown in Fig. 1, for they are quantized along the incident z axis of the *second* reaction; θ and ϕ are the usual polar and azimuthal angles for the second reaction, with xz plane lying in the plane of the first scattering. In this experiment the beam is scattered through 30° to the left in the laboratory by the "polarizer," and hence the new z axis is at an Euler angle $\beta=+30°$ in the original xz plane. If we ignore the small components $\langle T_{21}\rangle$ and

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[2] L. J. B. Goldfarb and J. R. Rook, Nuclear Phys. **12**, 494 (1959). These results are in substantial agreement with reference 1.

[3] R. J. N. Phillips, Phys. Rev. Letters **3**, 101 (1959).

[4] J. L. Gammel, B. J. Hill, and R. M. Thaler, Phys. Rev. **119**, 267 (1960).

[5] A. Galonsky and M. T. McEllistrem, Phys. Rev. **98**, 590 (1955).

[6] Lee G. Pondrom and J. W. Daughtry, a paper delivered at the 1960 Nucleon Polarization Conference in Basel, Switzerland, Suppl. Helv. Phys. Acta (to be published). See this report also for work done by Barloutaud *et al.* with higher energy polarized deuterons.

[7] A. Galonsky, H. B. Willard, and T. A. Welton, Phys. Rev. Letters **2**, 349 (1959).

[8] W. S. Porter, B. Roth, and J. L. Johnson, Phys. Rev. **111**, 1578 (1958).

[9] Albert Simon, Phys. Rev. **92**, 1050 (1953), Eq. (2.9). Our normalization of the tensors $\langle T_{qk}\rangle$ differs from Simon's.

[10] A similar formula has been written down by L. J. B. Goldfarb, Nuclear Phys. **12**, 657 (1958).