$N^{14}(n,t)$ and $N^{14}(n,d)$ Angular Distributions at 14.7 MeV

RICHARD H. LINDSAY AND J. J. VEIT
Department of Physics, Western Washington State College, Bellingham, Washington
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A triple-coincidence counter telescope consisting of two proportional dE counters and a solid-state E detector was used to study the angular distributions of tritons and deuterons for the ground-state transitions of N^{14} induced by 14.7-MeV neutrons. The relative triton-to-deuteron peak yield was found to be about 0.3. The (n,t) angular distribution is compared with pickup theory and with two other deuteron-transfer interactions between the ground states of N^{14} and C^{12}: the $N^{14}(\alpha, Li^6)$ and $N^{14}(d,\alpha)$ reactions. In these reactions the orbital angular momentum of the picked-up deuteron is principally $L=2$, with a smaller contribution from $L=0$ pickup suggested by the data. In addition, the $N^{14}(n,d)$ angular distribution is compared with the Gaussian-cutoff pickup theory, and with the $N^{14}(p,d)$ reaction to the ground state of the mirror nucleus N^{13}. The angular distributions, absolute magnitudes, and reduced widths of the two reactions are nearly identical, as expected. Cluster-model interpretations of the N^{14} data are discussed.

I. INTRODUCTION

IN the past two years, the angular distributions of tritons from the 14-MeV neutron bombardment of elements Li^6, Li^7, B^{10}, and F^{19} have been observed, these being the first detailed studies of such reactions.[1,2] The shapes of the angular-distribution curves to the low-lying states reflect a direct-interaction mechanism, the pickup of two nucleons. There are only a few light elements in which the (n,t) reaction could be observed at this energy, and N^{14} is one with a low Q value of -4 MeV. This is a particularly interesting target because there is evidence for at least two centers of symmetry within its nucleus, a core-plus-deuteron cluster structure.[3] Some of the evidence for this structure was obtained by Zafiratos,[4] who made a study of the $N^{14}(\alpha,Li^6)$ angular distributions with 42-MeV α particles. The angular distribution of the Li^6 ions was measured and compared with the same reaction in C^{12}. If the picked-up nucleon pair is correlated as a cluster in N^{14}, a higher probability of the cluster exchange should exist over the transfer of the same number of uncorrelated nucleons. A larger deuteron reduced width for N^{14} was observed by Zafiratos, about a factor of 5, and the angular distribution for the ground-state reaction suggested the pickup of two p-state nucleons from their correlated motion about the C^{12} core.

We would expect the $N^{14}(n,t)$ reaction to the ground state to follow about the same characteristics as the (α,Li^6). Indeed, there are other deuteron-transfer reactions with N^{14} which we would expect to follow the same pattern, the (d,α) and (p,He^3) reactions. A study of the angular distributions of α particles in the 21-MeV deuteron bombardment of N^{14} was made by Fischer and Fischer,[5] who found forward peaks in the ground-state angular distribution. The (p,He^3) reaction with N^{14} was investigated by MacLeod and Reid using a triggered cloud chamber.[6] They observed that the (p,He^3) total cross section contributes about 15% of the total cross section for all reactions with 13-MeV protons on nitrogen, but the angular distribution of the He^3 nuclei obtained was unsuitable for comparison with pickup theory because of insufficient counting statistics. These four reactions, involving the somewhat ideal pair of nuclei, N^{14} and C^{12}, give an extensive investigation of the deuteron-transfer process and the cluster structure of N^{14}.

Bromley[7] has given a thorough review of available data and their interpretation in deuteron-transfer reactions. Theories of the two-nucleon transfer reactions have been developed by El Nadi,[8] Newns,[9] and Glendenning.[10] Still lacking is a satisfactory theory of multinucleon pickup by the α particle. In this study, the (n,t) reaction is compared with other deuteron transfer reactions in N^{14}. We have used a two-nucleon pickup theory which introduces a radial Gaussian surface cutoff as a first approximation to the effects of the distorted-wave functions of the entrance and exit channels, in the evaluation of the appropriate matrix elements. The results leave the radial integrations dependent only upon the nuclear radius and the thickness of the surface region of interaction. A surface-thickness parameter λ can be adjusted for the best fit of the differential-cross-section theory to experiment, and is about 1 F. The differential cross sections for two-nucleon pickup by nucleons, deuterons, and α particles are given in the discussion of the data. In this study we have also investigated the ground-state angular distribution for the $N^{14}(n,d)$ reaction. Previous investigations of single-nucleon pickup reactions with this target have included both (p,d) and (n,d) angular-distribution measurements.

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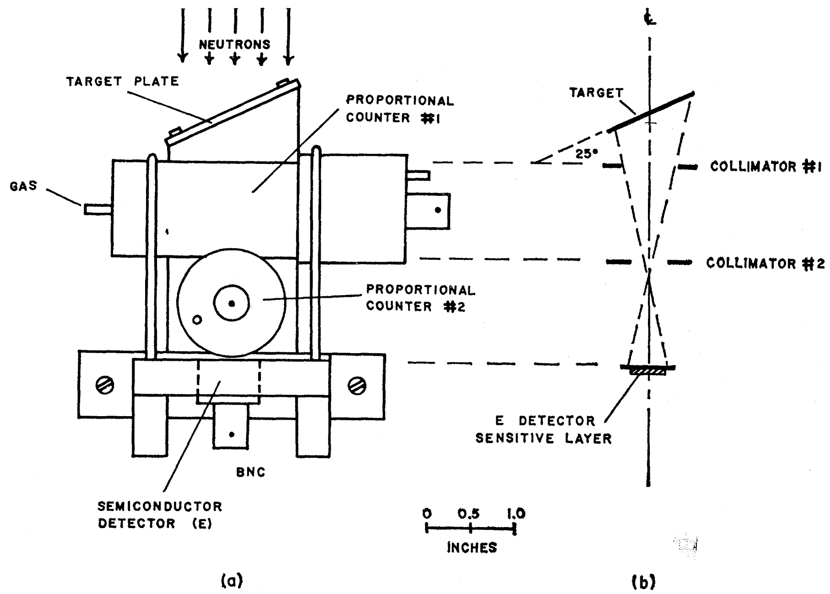

FIG. 1. Cross section of triple-coincidence counter telescope. Two identical lead-lined proportional counters and a 270-μ depletion-layer silicon detector were used. The NaN_3 target was inside the telescope and no windows are used. The neutron source was 5 in. from the target and consisted of a $\frac{1}{2}$-in.-diam spot on the Ti-T target.

$N^{14}(p,d)$ angular distributions were measured by Standing[11] at 18.7 MeV and later by Bennett[12] at 18.5 MeV. The first $N^{14}(n,d)$ angular distribution was obtained by Carlson[13] and later by Zatzick and Maxson,[14] both at 14 MeV. Changes of the angular distributions of these reactions with energy are not expected to be marked in this energy range.[12] In both these (n,d) studies, a triple coincidence counter telescope was used, with two gas proportional counters and a thin CsI scintillator for an E detector. In neither case was it clear that the over-all resolution and electronic particle identification techniques were adequate to separate the 9-MeV deuterons corresponding to the ground state (n,d) reaction from the 10-MeV tritons which could be present in the (n,t) ground state transition. Since tritons were not observed in these studies, it seemed advisable to repeat the $N^{14}(n,d)$ angular distribution work and to look for tritons. Since the (p,d) and (n,d) reactions with nitrogen are to mirror nuclei N^{13} and C^{13}, all these angular-distribution measurements are of interest for the interpretation of the data.

II. EXPERIMENTAL

Uniform, 40%-rich nitrogen targets were prepared on an aluminum foil by mixing silica gel with a saturated solution of sodium azide (NaN_3) in a 3:5 ratio by weight. The resulting mixture was then placed on the flat aluminum foil bordered on two sides by masking tape, then rolled and dried. Targets of thicknesses up to 15 mg/cm^2 gave adequate resolution of the ground-state data. The targets were bombarded by 14.7-MeV neutrons from the $H^3(d,n)He^4$ reaction with 150-keV deuterons in a neutron generator, and the neutron output was continuously monitored by a fast-neutron detector connected to a ratemeter and scaler. Average neutron fluxes near 10^7 neutrons/cm^2 sec were available at 10-cm distances from the end of the generator drift tube. Absolute fluxes were determined by activation of a Co^{59} foil, where the (n,α) cross section is well known.[15] The deuteron and triton data were collected simultaneously in 2-h runs at each angle, with the nitrogen target placed at a distance of 12.7 cm from the neutron source.

Figure 1 shows the counter telescope assembly and the target-detector geometry. The telescope consists of a target holder mounted with its normal at 25° to the beam direction, two lead-lined identical gas-flow proportional counters, and a silicon surface-barrier detector. The depletion layer of the E detector was chosen equal to the range of a 10-MeV triton. Methane gas at $\frac{1}{5}$ of an atmosphere was used in the proportional counters. The over-all resolution of the system was about 7%, with most of this due to target thickness. A 9-MeV deuteron loses about 200 keV in traversing the 7.5 cm average target to E-detector distance, and the corresponding energy loss for a 10-MeV triton is only slightly higher. The solid angle was determined by counting the α particles from a uniformly deposited Po^{210} source of known activity with the telescope evacuated and the source placed at the target position.

In Fig. 2 is shown a block diagram of the electronics, in which a $(dE/dx)\cdot E$ particle identification system using an XY oscilloscope was employed. The coincidence pulse intensifies the oscilloscope cathode-ray beam (Z axis) when the X (i.e., E) and the Y (dE) pulses are at their maximum. The result is a bright dot on the oscilloscope screen whose X and Y coordinates

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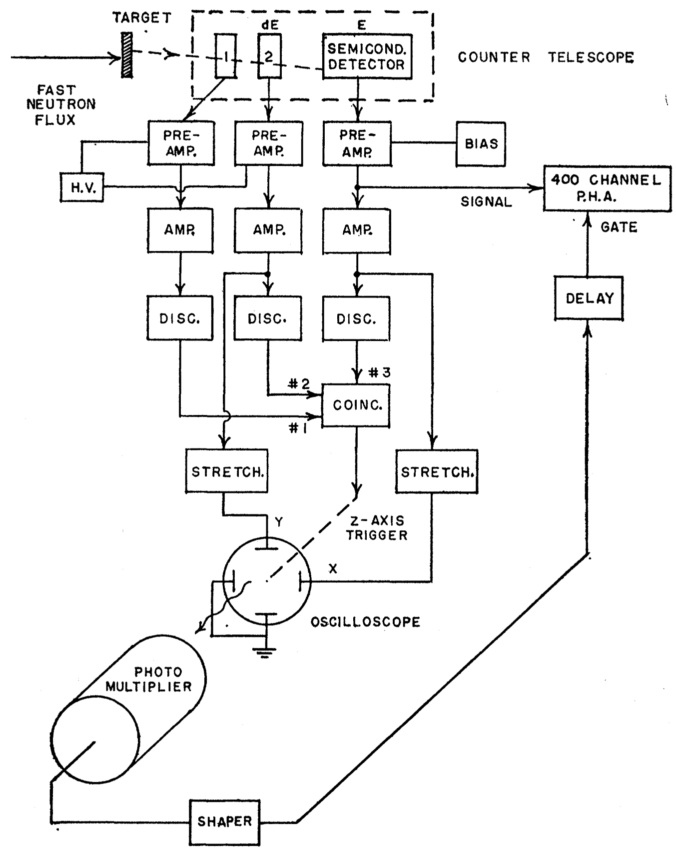

FIG. 2. Electronics employed for particle identification.

depend on the type and energy of the particle, with each type of particle being detected ultimately tracing out a hyperbolic pattern of dots. By appropriately masking the screen and viewing it with a 4-in. photomultiplier, an identification pulse corresponding to the type and energy of particles under investigation is generated, and used to gate a 400-channel analyzer. Selected energy spectra for the ground-state transitions of deuterons and tritons are shown in Fig. 3, at laboratory angles of 0° and 20°. All proton spectra were masked off and not analyzed. These spectra were taken simultaneously by gating on the ground-state groups in both the deuteron and triton hyperbolas. The triton and deuteron kinetic energies differ by about 1.2 MeV at 0° and 0.96 MeV at 50° laboratory angles. Background count rates under these peaks were between 10 and 20% of the total for the forward angles, and are subtracted out in Fig. 3. The background in the telescope at deuteron and triton energies below 6 MeV was substantially higher and made excited-state transitions difficult to measure. This background was mainly due to protons traveling backwards from the solid-state detector.

III. RESULTS AND DISCUSSION

A. $N^{14}(n,d)C^{13}$

A total of 14 experimental points between 0° and 60° in the $N^{14}(n,d)$ ground-state angular distribution are shown in Fig. 4. Counter background became of the order of the (n,d) yield above this angle. The differential cross section peaks at a center-of-mass (c.m.) angle of about 22°, near the same angle for the peak yield of the $N^{14}(p,d)$ reaction to the ground state of the mirror nucleus N^{13}. The error bars shown are from counting statistics only, and the measured differential cross section at 22° is 4.7 ± 1.7 mb/sr. The angular distribution is characterized by $L=1$ pickup, and is compared with the single-nucleon pickup theory in Fig. 4. A reasonable fit to the data with a nuclear-radius parameter of 5.6 F and a surface-cutoff parameter of 0.7 F is shown. The fit was about the same for surface-cutoff-parameter values up to 1 F.

In Fig. 5, the experimental (n,d) angular distribution is compared with the (p,d) angular distribution with 18.7-MeV protons measured by Standing.[11] The shape of the (n,d) angular distribution, the peak differential cross section, and the reduced width are all in agreement with Standing's (p,d) measurements. This is consistent, of course, with the principle of charge independence of nuclear forces. Since the picked up nucleon is most likely to come from outside the N^{14} core structure, the probability for the capture of the nucleon which forms the deuteron structure in the exit channel should be about the same for incoming protons or neutrons.

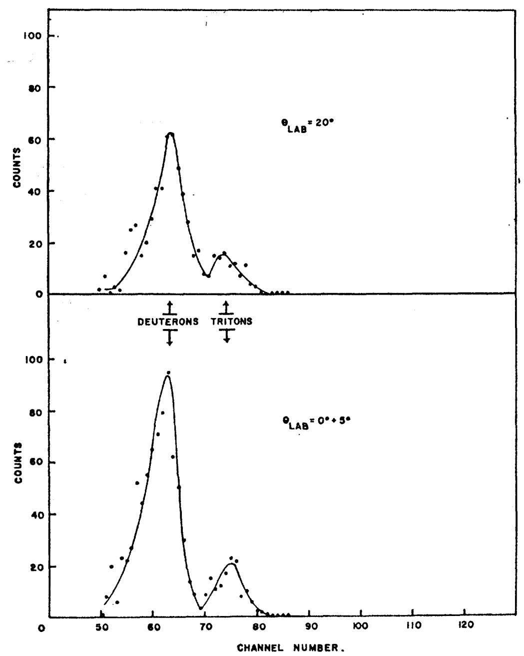

FIG. 3. Ground-state deuteron and triton energy spectra taken simultaneously at forward angles with a thick (15 mg/cm^2) NaN_3 target. Isolation of deuteron and triton groups is possible if one of the groups is masked off (see text).

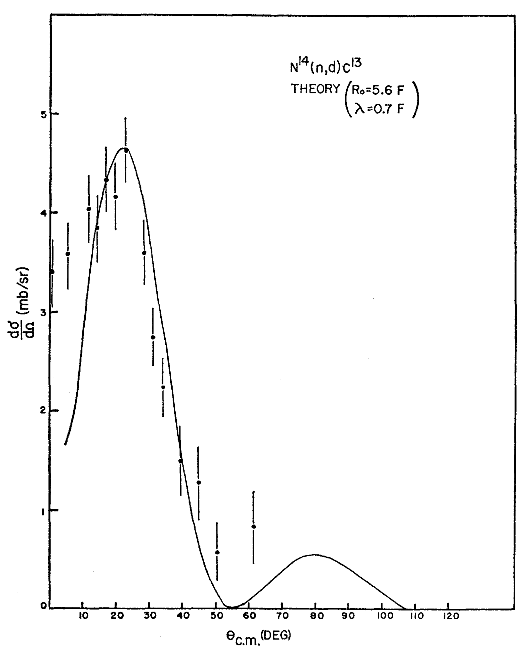

FIG. 4. Angular distribution for the ground-state $N^{14}(n,d)$ reaction and theory curve for $L=1$. Error bars shown are counting statistics and the theory is a Gaussian-cutoff distorted-wave approximation discussed in the text with a nuclear radius parameter of 5.6 F and a cutoff parameter of 0.7 F.

B. $N^{14}(n,t)C^{12}$

In Fig. 6, the experimental angular distribution for the $N^{14}(n,t)$ reaction to the ground state of C^{12} is shown. Two complete runs were taken under conditions of different geometry, with the N^{14} target placed at positions 8 and 12.7 cm from the source of neutrons. Although the results were substantially the same, the "good" geometry data (12.7 cm) are shown in Fig. 6. The differential cross-section peaks at a c.m. angle of about 30°, and the angular distribution is chiefly from $L=2$ pickup. The angular distributions of the two-nucleon pickup reactions are characterized by the total orbital angular momentum of the transferred deuteron, given by

$$\mathbf{J}_i+\mathbf{S}_i+\mathbf{L}=\mathbf{J}_f+\mathbf{S}_f; \quad \mathbf{L}=\mathbf{l}_n+\mathbf{l}_p.$$

Any substantial contribution from $L=0$ pickup would be manifested by a sharp rise in the cross section below 10°, which is not evident in the data. A small $L=0$ contribution to the yield was added in to fit the data below 10°, but this made no noticeable contribution to the theoretical angular distribution at higher angles. The theory curve for the $L=2$ transfer continues to drop below 15°, and the experimental points below this angle might be due to the usual problem in neutron angular distributions, defining a 0° beam. Experimentally, the ratio of the $L=0$ to $L=2$ contributions could be anywhere from 0 to $1/(2L+1)=\frac{1}{5}$, the weighting factor in the theoretical angular distribution (see below). A reasonable fit to the data was obtained for the parameters $R_0=5.6$ F and $\lambda=0.7$ F.

With the "deuteron" cluster model for N^{14}, the question arises as to what degree, if any, the cluster resembles the free nucleus. In the ground state of the deuterium free nucleus, the tensor force mixes a fraction of the ^3D-state wave function in with the ^3S-state wave function,

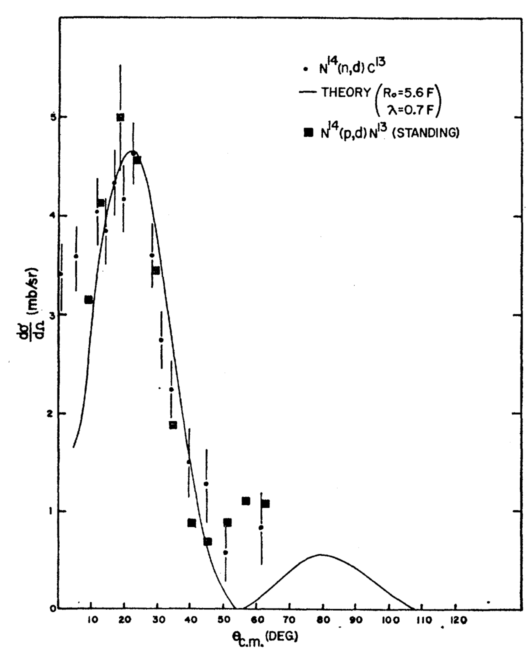

FIG. 5. Comparison of the $N^{14}(n,d)$ and $N^{14}(p,d)$ to the ground states of the mirror nuclei C^{13} and N^{13}. The angular distributions are in close agreement, as expected.

and the ^3D-state probability is about 4%. If the deuteron "cluster" in N^{14} resembled the free-deuteron nucleus, therefore, we would expect a substantial $L=0$ contribution to the angular distribution, where L is the orbital angular momentum of the picked-up deuteron. Since the important quantitative contribution to the angular distribution is $L=2$, it must be concluded that the residual interaction between the cluster and the core substantially changes the ^3S-^3D mixture in N^{14} from that of the free deuteron.

Given below are the results of the calculations for the differential cross sections for two-nucleon pickup theory for protons, deuterons, and α particles. We have used the Gaussian form for the internal wave functions of the deuteron and the α particle, and cluster-structure wave functions for Li^6. Amplitude distortion in the wave functions was introduced through a radial Gaussian surface cutoff after the manner of McCarthy and Pursey.[16] A FORTRAN program for the calculations of the differential cross sections was set up on the IBM 1620 computer.

IV. TWO-NUCLEON PICKUP THEORY

A. By Nucleons

$$\frac{d\sigma}{d\Omega}\propto\frac{k_f}{k_i}\frac{(2j_f+1)}{(2j_i+1)}\sum_L(2L+1)A_L{}^2F^2(Q,R_0,\lambda)G^2(K),$$

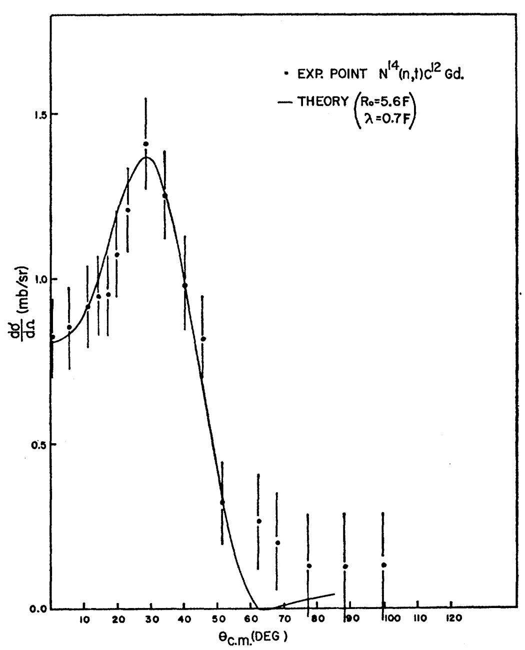

FIG. 6. Angular distribution of tritons in the $N^{14}(n,t)$ ground-state reaction. The two-nucleon pickup-theory parameters used are the same as the $N^{14}(n,d)$. The peak yield is near $\theta_{c.m.}=30°$. The total cross section for the ground-state transition is about 2 mb.

[16] I. E. McCarthy and D. L. Pursey, Phys. Rev. 122, 578 (1961).

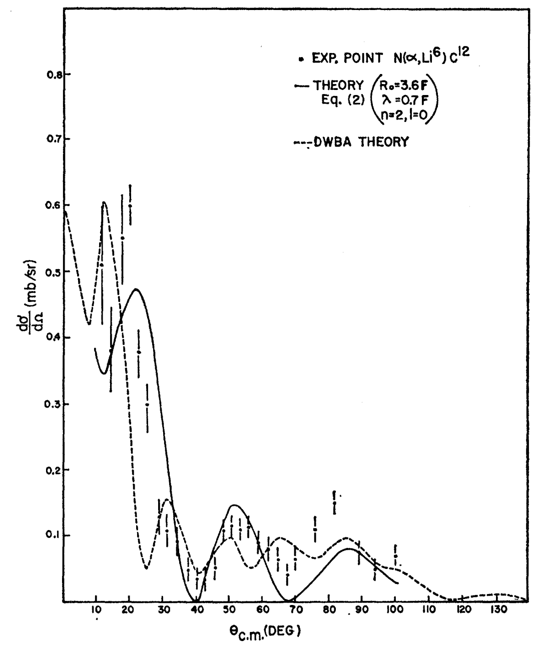

FIG. 7. Angular distribution for the $N^{14}(\alpha,Li^6)$ reaction to the ground state of C^{12} measured by Zafiratos (Ref. 4). A theoretical fit is shown for the Gaussian-cutoff distorted-wave pickup theory [Eq. (2)] for $R_0=3.6$ F and $\lambda=0.7$ F. There are no significant changes in the fits for values of λ between 0.7 and 1.0 F. Shown also is a DWBA fit to the $N^{14}(\alpha,Li^6)C^{12}$ angular distribution made by Zafiratos (Ref. 4).

where

$$F(Q,R_0,\lambda)=\int_0^\infty \exp[-(R-R_0)^2/\lambda^2]j_L(QR)R^2dR,$$

$$G(K)=\int_0^\infty \exp(-2\gamma_t{}^2u^2)j_0(Ku)u^2du, \tag{1}$$

$$\mathbf{Q}=\mathbf{k}_i-(m_i/m_f)\mathbf{k}_f,$$

and

$$\mathbf{K}=\tfrac{2}{3}(\mathbf{k}_i+(m_n/m_f)\mathbf{k}_f).$$

B. By Alpha Particles

$$\frac{d\sigma}{d\Omega}\propto\frac{k_f}{k_i}\frac{(2j_f+1)}{(2j_i+1)}\sum_L(2L+1)A_L{}^2F^2(Q,R_0,\lambda)G^2(K,n,l),$$

where

$$F(Q,R_0,\lambda)=\int_0^\infty \exp[-(R-R_0)^2/\lambda^2]j_L(QR)R^2dR,$$

$$G(K,n,l)=\int_0^\infty \exp(-\gamma^2u^2)j_l(Ku)u^{n+2}du, \tag{2}$$

$$\mathbf{Q}=\mathbf{k}_i-(m_i/m_f)\mathbf{k}_f,$$

and

$$\mathbf{K}=\tfrac{1}{3}(\mathbf{k}_i+(M_\alpha/M_f)\mathbf{k}_f).$$

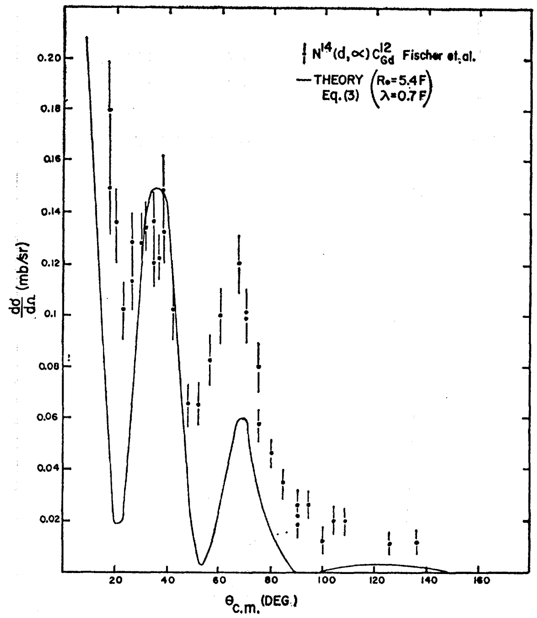

FIG. 8. The $N^{14}(d,\alpha)C^{12}$ angular distribution measured by Fischer *et al.* (Ref. 5) compared with pickup theory. The best fits to the data are for parameters which are about the same as the $N^{14}(n,d)$ and $N^{14}(n,t)$.

C. By Deuterons

$$\frac{d\sigma}{d\Omega}\propto\frac{k_f}{k_i}\frac{(2j_f+1)}{(2j_i+1)}\sum_L (2L+1)A_L{}^2F^2(Q,R_0,\lambda)G^2(K)\,,\quad(3)$$

where F = same as above,

$$G(K)=\int_0^\infty \exp(-4\gamma_\alpha{}^2u^2)j_0(Ku)u^2du\,,$$

$$\mathbf{Q}=\mathbf{k}_i-(m_i/m_f)\mathbf{k}_f\,,$$

$$\mathbf{K}=\tfrac{1}{2}(\mathbf{k}_i+(m_d/m_f)\mathbf{k}_f)\,.$$

We have used Eqs. (1)–(3) in comparing the experimental angular-distribution work with theory. The function $G(K)$ does not change markedly with angle, nor is it very sensitive to choices of the triton and α range parameters γ_t^{-1} and γ_α^{-1} for two-nucleon pickup by nucleons and deuterons. However, in the case of (α,Li^6) reactions, the function $G(K)$ increases somewhat rapidly over the angular range from zero to 90°, by about a factor of 8. This raises the diffraction peaks which occur at higher angles for the $N^{14}(\alpha,Li^6)$. Experimentally, we note in Fig. 7 that the third diffraction peak (at 85°) is about as high as the second, which is not predicted by the Butler theory. The choice of range parameter γ in Eq. (2) was the same as chosen in the cluster structure work of Pearlstein *et al.*,[17] with $\gamma^2=0.20232$ F^{-2}. In Eq. (2), n and l are the Li^6 cluster wave function parameters, $n=2$ and $l=0$.[17]

In Fig. 7, the experimental angular distribution for the $N^{14}(\alpha,Li^6)$ reaction to the ground state of C^{12} is shown. The measurements with 42-MeV α particles were made by Zafiratos.[4] The theoretical fit to the data shown in Fig. 7 is for parameters $R_0=3.6$ F and $\lambda=0.7$ F. A critical question concerning the data is whether there is a true rise for small angles. The point at 11° does indicate a rise in the differential cross section, but unfortunately it is only one point and the counting statistics overlap this point with one at 15°. A substantial $L=0$ contribution will give a sharp rise below 10°, according to the theory used here, and a secondary, much smaller bump in the cross section would appear around 34°. There is a slight rise in the cross-section data at about 34°, but is is clear that more data should be taken. The theoretical fit shown is the addition of an $L=0$ and an $L=2$ contribution with their appropriate statistical weights $(2L+1)$. Figure 7 shows a distorted-wave Born-approximation (DWBA) calculation made by Zafiratos.[4] Equation (2) fits the diffraction minima and maxima more precisely than the DWBA choice of parameters made by Zafiratos.

The $N^{14}(d,\alpha)C^{12}$ reaction has been studied by Fischer *et al.*,[5] at 21 MeV. The data and a theoretical calculation are shown in Fig. 8. In this case the data more clearly indicate a rise in the cross section for small angles and a first $L=2$ peak at 30–35°. The differential cross section versus θ is much like the (α,Li^6), with two clear diffraction peaks. Again the theory shown is the addition of an $L=0$ and an $L=2$ term with the appropriate statistical weight. Both the (d,α) and the (n,t) have peaks near 30°, and cross-section minimum values near 55°.

The deuteron transfer reactions between the ground states of N^{14} and C^{12} have marked similarities as seen in their angular distributions. Of the three reactions discussed here, the (d,α) has the smallest differential cross section, possibly because of the fact that all spins are zero in the exit channel for this reaction, and there are only a limited number of ways that this may be accomplished compared to the (n,t) and (α,Li^6) reactions. A more extensive use of DWBA calculations for the neutron-induced reactions is forthcoming.[18]

ACKNOWLEDGMENTS

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[17] L. D. Pearlstein, Y. C. Tang, and K. Wildermuth, Nucl. Phys. **18**, 23 (1960).

[18] P. Fessenden and D. R. Maxson, Phys. Rev. (to be published), and (private communication).