PHYSICAL REVIEW VOLUME 158, NUMBER 4 20 JUNE 1967

$N^{14}(n,d)C^{13}$, $N^{14}(n,t)C^{12}$, and $N^{15}(n,d)C^{14}$ near $E_n=14$ MeV[*][†]

P. Fessenden[‡] and D. R. Maxson
Brown University, Providence, Rhode Island

(Received 4 November 1966)

A triple-coincidence counter telescope consisting of two thin silicon surface-barrier dE/dx detectors (114 μ total thickness) and a CsI E detector was used with a pulse-multiplier particle-discrimination system to detect the charged particles emanating from nuclear reactions induced by 14.1- or 14.8-MeV neutrons. Angular distributions of the outgoing charged particles from the ground-state transitions of $N^{14}(n,d)C^{13}$ and $N^{14}(n,t)C^{12}$ were measured out to a center-of-mass angle of 100° for 14.1-MeV incident neutrons. The (n,d) distribution was fitted with two $l=1$ theoretical curves calculated from the Butler and distorted-wave Born-approximation (DWBA) theories. The (n,t) results were fitted by two $l=2$ curves calculated from the double-stripping theory of Newns and the diffraction theory of Dar, and were compared to previous results obtained for $C^{12}(He^3,p)N^{14}$. Charged particles corresponding to the excited-state transitions $N^{14}(n,d)C^{13}$ ($E_x=3.68$ MeV) and $N^{14}(n,t)C^{12}$ ($E_x=4.43$ MeV) were detected at forward angles. Angular distributions for the $N^{15}(n,d)C^{14}$ ($E_x=0$) reaction were measured out to 60 degrees for $E_n=14.1$ and 14.8 MeV. The 14.8-MeV data were fitted with Butler and DWBA curves for $l=1$, but the 14.1-MeV data were inconsistent with a pure-direct-reaction interpretation. The results agree with previous measurements on the inverse $C^{14}(d,n)N^{15}$ reaction, and indicate that a compound-nucleus mechanism contributes strongly near 14.9 MeV of excitation in the N^{16} compound nucleus. Absolute reduced widths θ^2 and spectroscopic factors C^2S were extracted from the fits to the $N^{14,15}(n,d)$ ($E_x=0$) reactions.

I. INTRODUCTION

For over a decade, the study of angular distributions of nucleon-transfer reactions, interpreted with direct-reaction theories, has been used as a valuable tool in the field of nuclear spectroscopy. Although hundreds of such reactions have been reported, there has always been a conspicuous lack of (n,d) reaction experiments. This has been due to the experimental difficulties arising from the necessity of using a point source of highly penetrating particles (neutrons), and from the negative Q values (usually greater than several MeV) characteristic of (n,d) reactions. As a result of advances in experimental techniques, particularly those associated with fast timing and pulse multiplication, the number of reported (n,d) angular distributions has tripled since 1960. The target isotopes which have been reported[1–6] include Li^6, B^{10}, N^{14}, O^{16}, F^{19}, Na^{23}, Al^{27}, P^{31}, $S^{32,34}$, Ti^{48}, V^{51}, $Fe^{54,56}$, Ni^{58}, Cu^{63}, and Zn^{64}. For all cases except[2] Na^{23}, ground-state results, and often those for several excited states, are well fitted in the region of the first maximum with a characteristic Butler "stripping" curve and/or a distorted-wave Born-approximation[3] (DWBA) stripping curve.

Multinucleon transfer reactions, particularly those involving transfer of two nucleons, have received increasing attention in recent years. Again, and for the same reasons as in the (n,d) case, there is a noticeable paucity of (n,t) reaction measurements. When the present work was undertaken, the $Li^{6,7}(n,t)$, $F^{19}(n,t)$ and $B^{10}(n,t)$ angular distributions had been reported[6,7] and only in the latter case had there been an attempt to explain the shape of the angular distribution. [Very recently, additional work has been done on the $N^{14}(n,t)$ reaction, and, apart from absolute magnitudes, the results appear in agreement with the present paper.[8]]

Although the $N^{14}(n,d)C^{13}$ reaction had been investigated previously,[4,5] it was chosen for study because the previous experiments were not able to discriminate very well against competing tritons of nearly the same energies as the deuterons of interest. Concurrent measurements of $N^{14}(n,t)C^{12}$ seemed promising because of the relatively favorable Q value (-4.015 MeV). The other stable isotope of nitrogen, N^{15}, had not been reported as a target in neutron-induced reactions, so it appeared worthwhile to investigate the $N^{15}(n,d)C^{14}$ reaction. In jj shell-model coupling, the two (n,d)

---

[*] This work was supported in part by the U. S. Atomic Energy Commission.

[†] Based on a thesis submitted in partial fulfillment of the requirements for the degree of Doctor of Philosophy at Brown University.

[‡] Present address: Department of Physics, Oregon State University, Corvallis, Oregon.

[1] F. L. Ribe, Phys. Rev. **106**, 767 (1957); F. L. Ribe and J. D. Seagrave, *ibid.* **94**, 934 (1954); G. E. Velyukhov, A. N. Prokof'ev, and S. V. Starodubtsev, Zh. Eksperim. i Teor. Fiz. **39**, 563 (1961) [English transl.: Soviet Phys.—JETP **12**, 395 (1961)]; L. Colli, M. G. Marcazzan, F. Merzari, P. G. Sona, and F. Tonolini, Nuovo Cimento **16**, 991 (1960); I. Šlaus, P. Tomaš, and N. Stipcic, Nucl. Phys. **22**, 692 (1961); R. N. Glover and E. Weibold, *ibid.* **24**, 630 (1961); R. N. Glover and K. H. Purser, *ibid.* **24**, 431 (1961); E. Gadioli and S. Micheletti, Phys. Letters **6**, 229 (1963); L. Colli, P. Forti, and E. Gadioli, Nucl. Phys. **54**, 253 (1964).

[2] Bunzabro Saeki, Nucl. Phys. **73**, 631 (1965).

[3] K. Ilakovac, L. G. Kuo, M. Petravic, I. Šlaus, P. Tomaš, and G. R. Satchler, Phys. Rev. **128**, 2739 (1962); V. Valković, G. Paić, I. Šlaus, P. Tomaš, M. Cerineo, and G. R. Satchler, *ibid.* **139**, B331 (1965); L. Colli, E. Gadioli, S. Micheletti, and D. Lucioni, Nucl. Phys. **46**, 73 (1963); G. Bassani, L. Colli, E. Gadioli, and I. Iori, *ibid.* **36**, 471 (1962); R. R. Wagner and R. A. Peck, Jr., Bull. Am. Phys. Soc. **11**, 349 (1966); W. N. Wang and E. J. Winhold, Phys. Rev. **140**, B882 (1965).

[4] R. R. Carlson, Phys. Rev. **107**, 1094 (1957).

[5] M. R. Zatzick and D. R. Maxson, Phys. Rev. **129**, 1728 (1963).

[6] G. M. Frye, Jr., Phys. Rev. **93**, 1086 (1959); J. B. Weddell and J. H. Roberts, *ibid.* **95**, 117 (1954).

[7] V. Valković, Nucl. Phys. **54**, 465 (1964); V. Valković and P. Tomaš, in *Proceedings of the International Conference on Nuclear Physics, Paris, 1964* (Editions du Centre National le la Recherche Scientifique, Paris, 1965), Vol. 2, p. 936.

[8] R. H. Lindsay and J. J. Veit, Bull. Am. Phys. Soc. **11**, 736 (1966), and (private communication).

ground-state transitions are expected to be similar since they both involve $l=1$ transfer of a $(1p_{1/2})$ proton.

II. EXPERIMENTAL PROCEDURE

A 200-keV beam of deuterons from the Brown University accelerator was used to produce an average flux of 10^9 neutrons/sec (into 4π) by means of the $T(d,n)He^4$ reaction. The 14.1-MeV neutrons result when the experimentally convenient angle of 90° between the deuteron beam and the outgoing neutrons is used. A second bombarding energy of 14.8 MeV was obtained by utilizing the neutrons which were emitted in the same direction as the accelerator deuteron beam. Unlike the nearly monoenergetic 14.1-MeV neutrons, the higher-energy neutrons had a kinematic spread of 500 keV for the thickness of the Ti-T target used.[9] The neutrons were monitored by counting the associated alpha particles from the $T(d,n)He^4$ reaction. The detector was a *p-n* junction silicon counter of small solid angle, just thick enough to stop the 3.5-MeV alphas.

The charged particles of interest produced in the neutron-induced reactions were detected with the triple-coincidence counter telescope shown in Fig. 1. The dE/dx_1 and dE/dx_2 counters were totally depleted transmission-type detectors obtained from Oak Ridge Technical Enterprises Corporation. They had areas of 100 and 150 mm² and thicknesses of 49 and 65 μ, respectively. The E detector was a CsI(Tl) crystal just thick enough (0.045 in.) to stop the maximum-energy protons expected. It is desirable to have the volume of the E detector as small as possible since one of the main sources of background consists of E-detector pulses in chance coincidence with true dE/dx_1-dE/dx_2 coincidences. The counters were lined with high-purity graphite in order to cut down on background particles from the counter walls and other surfaces. The nuclear reaction Q values are such that the only particle of significant energy produced by 14.1-MeV neutrons incident on C^{12} (C^{13}) is an alpha particle of 8-MeV (10-MeV) maximum energy. The front end of the telescope contained a target wheel which conveniently allowed any one of six reaction, background, or calibration targets to be rotated into position with no scattering or energy absorbing material between target and dE/dx_1 detector. The usual target-to-neutron source distance was 2.0 in., and the solid angles subtended by the target at the source and by the E detector at the target were 0.0137 and 0.0142 sr, respectively. The telescope could be swung through a laboratory angle of about 85° with this configuration, and the angular range could be doubled when the telescope was moved back an additional 2 in. from the source.

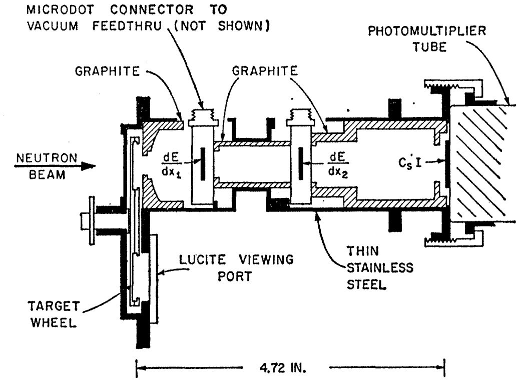


FIG. 1. Cross section of triple-coincidence counter telescope. The CsI crystal was loosely covered with a 0.025-mil nickel foil (not shown). The full-width half-maximum angular resolution of the telescope at a 15° setting was 10°.

The decision to use an all solid-state counter telescope was motivated by the several definite advantages with regard to gain stability, definition of time of a nuclear event, and statistics of energy loss, which such a unit has over one employing gas proportional counters. Also, the all-solid-state telescope avoids the use of gas-confining windows, presents a less serious problem of multiple scattering (per unit of particle energy loss, due to the small distances involved between collisions), and can tolerate higher counting rates because of the fast recovery of a silicon detector.

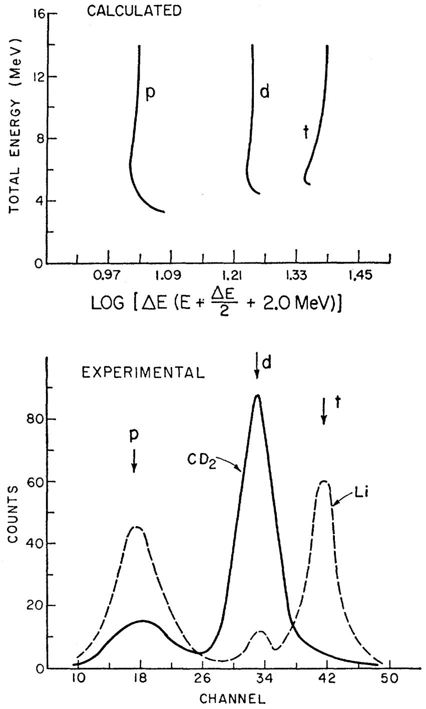
Unfortunately the solid-state telescope is not without its disadvantages, including the possibility of sudden failure of the silicon detectors and their otherwise limited useful lifetimes[10] of 10^{12}–10^{13} neutrons/cm². Of more importance for this particular experiment were the disadvantages caused by detector noise, fixed dE/dx thickness, and neutron-induced background counts. The dE/dx detectors considered together had a full-width at half-maximum (FWHM) noise figure of about 60 keV, which was relatively small compared to the over-all 200-keV energy resolution of the total ΔE energy spectra. However, this noise together with the aggregate 50-keV noise contributed by the two dE/dx preamplifiers resulted in a ± 0.2 μsec uncertainty in the timing of the dE/dx pulses. This necessitated the use of a large coincidence resolving time (equal to 0.5 μsec) and thereby affected an increase in the chance coincidence rate, especially at the high counting rates experienced at large scattering angles. (This effect of noise on the time resolution was not anticipated, and the design of the telescope did not provide for good cooling, which is necessary for noise reduction.) The total ΔE thickness of 114 μ imposed serious lower limits of about 4.5 and 5.2 MeV for the deuterons and tritons, respectively, that could be detected. The proton background associated with the telescope was moderate, as expected from published cross sections,[11] but the good mass discrimination of the over-all system prevented any

---

[9] J. D. Seagrave, Los Alamos Report 2162, 1957 (unpublished).

[10] G. Dearnaley, Nucleonics **22**, (1964).

[11] F. L. Hassler and R. A. Peck, Jr., Phys. Rev. **125**, 1011 (1962).



LOGARITHMIC CONVERSION OUTPUT

FIG. 2. Calculated values of the logarithm of the product of ΔE and $(E+\frac{1}{2}\Delta E+2.0)$ as a function of particle type and energy (upper curve). The lower curve is a composite of experimental spectra of the logarithmic converter output with particles detected spanning the full energy range of interest.

proton contamination of the deuteron or triton spectra from this source. The triton background was negligible, but the deuteron background was serious at low deuteron energies. The source of this deuteron background was the $\mathrm{Si}^{28}(n,d)\mathrm{Al}^{27}$ ($Q=-9.36$ MeV) reaction in the dE/dx_1 counter acting as both target and detector. From a knowledge of the minimum energy losses which must be deposited in the dE/dx_1 and E counters for an event to be recorded, the effective target thickness of the dE/dx_1 counter was determined to be 6.3 mg/cm^2. This leads to an estimated cross section of 5.3 mb/sr ±40% for the $\mathrm{Si}^{28}(n,d)\mathrm{Al}^{27}$ reaction at 6° (center of mass). Originally the intent was to use a silicon detector for the E counter also. With this type of detector, however, the low-energy deuteron background would have been approximately tripled due to $\mathrm{Si}^{28}(n,d)$ events originating in the thick E detector and passing throgh the two dE/dx detectors. The observations concerning the use of silicon detectors in a counter telescope in the present experiment are in accord with the recent excellent discussion of counter telescopes by Paić *et al.*[12]

The dE/dx_1 and dE/dx_2 pulse outputs, after suitable preamplification, were fed along with the E detector pulse to a pulse multiplier particle identification system. This system has been fully discussed previously.[13] The unit attenuated the three pulses so that their sizes were proportional to the energy losses they represented, and sent their sum (the total energy pulse) to a Radiation Instrument Development Laboratory 400 channel analyzer. The analyzer was gated by the output of a fast "crossover" coincidence circuit, and the total energy pulse was routed to a particular quarter of the analyzer depending on the mass of the particle being detected. The mass discrimination was effected by height selection of pulses representing the product of ΔE and $(E+f\Delta E+C)$, as generated by addition of the logarithms of the pulses corresponding to the two factors. ΔE is the total $dE/dx_1+dE/dx_2$ energy loss and E is the energy deposited in the CsI crystal. The optimum values of f and C for this experiment were $\frac{1}{2}$ and 2.0 MeV, respectively. The upper part of Fig. 2 shows the theoretical dependence of the pulse multiplier output on the energy and particle type. The lower half of the figure presents experimental spectra obtained with thick targets of deuteroparaffin (CD_2) and natural lithium. These thick targets yielded protons, deuterons, and tritons over the entire ranges of interest of 3–14 MeV, 4–12 MeV, and 5–10 MeV, respectively. The nonlinearity of the low-energy part of the theoretical curves and a large part of the broadening in the experimental spectra reflect the rapid rise of dE/dx at particle energies approaching total absorption in the dE/dx counters. Under actual running conditions, where only a limited range of energy was of interest, the corresponding $\Delta E(E+\frac{1}{2}\Delta E+2.0$ MeV) spectra were much cleaner. The resulting foldovers of a given type of particle into the energy spectra of other types depended on the type of particle of interest and the particular discriminator settings used, but were within the range 0.5–9% for all measurements. This inability to discriminate perfectly between particle types originated from the finite resolutions of the counters. The E counter had a resolution of 5% to particles in the 3–15-MeV range and the ΔE counters (together) had a resolution of 25% for 14-MeV protons and 16% for 12-MeV deuterons. One of the routed sets of spectra, corrected for background, is shown in Fig. 3. The "residuals" section recorded those particles not routed to the *p*,*d* or *t* quarters of the analyzer, and thus provided a record of the particles lost. These spectra were taken under conditions where the electronics were ajusted for maximum discrimination between low-energy deuterons and tritons.

Several targets employing nitrogen in its natural form (99.6% N^{14}) were used for the N^{14} reactions. The first targets were fabricated by melting crushed crystals of urea $[(\mathrm{NH}_2)_2\mathrm{CO}]$ on a lead blank. Two targets with areal densities of 3.4 and 9.4 mg/cm^2 were made in this manner. The reaction Q values of carbon and oxygen are such that their presence merely added to target

---

[12] G. Paić, I. Šlaus, and P. Tomaš, Nucl. Instr. Methods **34**, 40 (1965).

[13] J. M. Kootsey, Nucl. Instr. Methods **35**, 141 (1965).

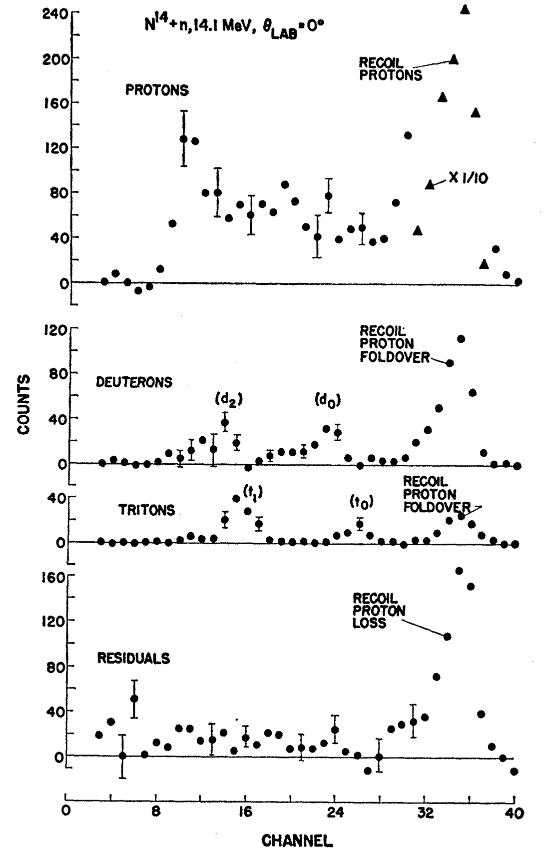


FIG. 3. Routed energy spectra, corrected for background, resulting from 14.1-MeV neutrons incident on the 3.4-mg/cm^2 natural urea target. The counter setting was 0°. The deuteron and triton peaks identified are from the N^{14} in the target. The "recoil proton" groups resulted from the elastic scattering of the incident neutrons on the hydrogen present in the target.

thickness, but a minor problem with urea was that it sublimes in vacuum.[14] This property was checked in the present experiment, and it was determined that the weight of the urea decreased by about 1% for each 20 h that the target was in vacuum. A worse problem turned out to be recoil protons resulting from the hydrogen present in urea. These had the same energy as some of the deuteron groups of interest at scattering angles near 40–55°, so that a proton foldover rate of only 0.5–1% was serious. Therefore, some of the data were secured with a target of melamine ($C_3H_6N_6$), which has a nitrogen:hydrogen ratio of twice as great as that of urea. A very uniform target of 6.0 mg/cm^2 was fabricated by letting a suspension of ether and crushed melamine settle out. The absolute areal density of the melamine could be determined to within about 3%. The urea targets, however, had poorly defined edges, so that their areal densities could not be found accurately by weighing. Accordingly, their thicknesses were determined by measuring the recoil proton yield at several forward angles. Agreement within experimental error was obtained when the same measurement was made with two or three of the different targets.

The N^{15} targets were made from a sample of N^{15}-enriched urea obtained from Isomet Corporation. The N^{15} enrichment was 96.6%, which leads to a N^{15}:N^{14} ratio of 29:1. A large ratio is desired because the $N^{14}(n,d)C^{13}$ ($E_x = 3.68$ MeV) reaction yields a deuteron group that is about 1 MeV below the ground-state deuteron group from $N^{15}(n,d)C^{14}$. Targets of 8.0 and 4.0 mg/cm^2 were fabricated. The latter had an exceptionally well-defined area and the recoil proton cross section based on this target's areal density agreed to within 4% with the published value.[15]

Several types of corrections were incorporated into the analysis of the experimental data. The raw-energy spectra, corrected for background, are really distortions of the true spectra because of foldovers among particle types and losses resulting from trying to minimize these foldovers. However, these effects could be accounted for exactly (except for the resulting increases in statistical errors) by prudent selection and accurate measurement of the foldover and loss rates. For this purpose, auxiliary measurements were performed using recoil protons from polyethylene and recoil deuterons plus protons from deuteroparaffin. A correction was also required because of the attenuation of the neutron flux prior to its incidence on the reaction target. Total cross-section data,[16] as well as experimental determinations obtained by placing various absorbers in the neutron "beam," indicated that 8.7% of the original beam was affected as a result of its passing through the neutron-source mechanical housing and circulating water cooling. There was also an additional 3.4% loss of primary neutrons (with the telescope at 0°) due to the telescope housing and reaction target backing. A third correction was needed to account for the automatic averaging of the cross section over a range of angles which takes place due to the finite solid angles of the counters. In order to account for this effect the theoretical curves had to be smeared over a range of reaction angles for each counter angle, with a weighting factor proportional to the detection efficiency at each reaction angle. This weighting factor, or aperture function, was calculated[17] on an IBM-7070 computer. The application of similar smearing corrections has been discussed in Ref. 5.

The cross-section values reported here are absolute, and the errors shown include those averaged from four sources: target thickness (±3%); number of neutrons produced (±2.5%); counter geometry (±3%); and counting statistics (±5% to ±60%, depending on the number of counts observed and the magnitude of the background, loss, and foldover corrections).

---

[14] C. R. Noller, *Structure and Properties of Organic Compounds* (Saunders Company, Philadelphia, 1962), p. 138.

[15] H. L. Poss, E. O. Salant, G. A. Snow, and L. C. L. Yuan, Phys. Rev. **87**, 11 (1952).

[16] D. J. Hughes and R. B. Schwartz, *Brookhaven National Laboratory Report No. 325* (U. S. Government Printing and Publishing Office, Washington, D. C., 1957), Suppl. 1.

[17] J. M. Kootsey, Brown University, 1964 (unpublished).

TABLE I. Particle energies.

Reaction	Q value (MeV)	Laboratory energy (in MeV) of outgoing particle at 0° for 14.1-MeV neutrons
$N^{14}(n,d)C^{13}$ ($E_x=0$)	−5.32	8.76
($E_x=3.68$ MeV)	−9.00	5.07
$N^{14}(n,t)C^{12}$ ($E_x=0$)	−4.01	9.85
($E_x=4.44$ MeV)	−8.45	5.63
$N^{15}(n,d)C^{14}$ ($E_x=0$)	−7.98	6.11
($E_x=6.09$ MeV)	−14.07	0.00
$N^{15}(n,t)$ ($E_x=0$)	−9.90	4.22

III. RESULTS AND DISCUSSION

$N^{14}(n,d)C^{13}$ ($E_x=0$)

Table I illustrates why good particle discrimination is necessary for an accurate determination of the absolute differential cross sections for the $N^{14}(n,d)$ and (n,t) reactions. Reference 5 gives a full discussion of these problems and states that the probable upper limit to triton contamination of the ground-state deuteron angular distribution reported there is 15%. However, no figure is given for contamination of an excited-state deuteron group by tritons.

Figure 4 shows the angular distribution obtained in the present experiment for ground-state deuterons with 14.1-MeV neutrons incident. The large error bars on the data points near 50° reflect worsening statistics due to foldover of recoil protons into the deuteron spectrum. The increase in statistical uncertainty at the largest angles resulted from the high chance coincidence rate encountered as the counter telescope approached the neutron source. Except for a 15–20% reduction in magnitude in the vicinity of the peak, the distribution is very similar to those previously reported by Carlson[4] and by Zatzick and Maxson.[5] The Butler curve for $l=1$ and a radius of 5.36 F fits the peak well. (Since N^{14} and C^{13} have spins of 1^+ and $\frac{1}{2}^-$, respectively, only $l=1$ is allowed by the conservation of angular momentum and parity.) The absolute reduced width θ^2 extracted from this Butler curve using the method of Macfarlane and French[18] is 0.042±10%. This value is somewhat lower than Refs. 4 and 5 report (0.05 and 0.065, respectively), but in view of their concern about triton contamination, it is not surprising that lower values for the reduced width and cross section are found in the present experiment. The value of 0.042 agrees well with the value of $\theta^2=0.046$ measured for the mirror $N^{14}(p,d)N^{13}$ reaction.[18,19] The spectroscopic factor S may be obtained by dividing θ^2 by the single-particle reduced width θ_0^2, an empirically determined parameter introduced by Macfarlane and French to absorb the shortcomings of the Butler theory. θ_0^2 for the region of the $1p$ shell involved here is 0.046, which gives $S=0.92\pm10\%$. (The value for the experimental spectroscopic factor in a formalism without isotopic spin would be this value multiplied by $C^2=\frac{1}{2}$, where C is an isotopic-spin coupling coefficient.) Extreme jj coupling gives a value of $S=2$ since this transition involves the pickup of one of two equivalent $(1p_{1/2})$ nucleons. Since it is known that intermediate coupling provides a better explanation of this region of the $1p$ shell, it is not surprising that the jj value of S differs from the measured value.

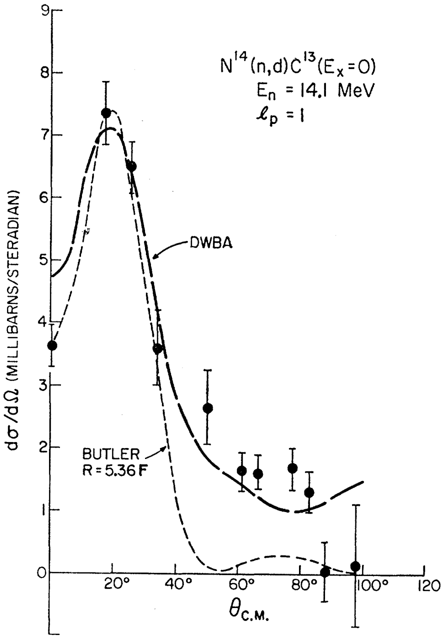


FIG. 4. Angular distribution of $N^{14}(n,d)C^{13}$ (ground state) with 14.1-MeV neutrons incident. The theoretical curves are normalized.

TABLE II. Optical-model parameters.[a]

$$U_x=\frac{V_x+iW_x}{1+\exp[(r-r_{0x}A^{1/3})/a_x]}+V_{\text{Coulomb}}.$$

Reaction	$N^{14}(n,d_0)C^{13}$	$N^{15}(n,d_0)C^{14}$
Dominant-target configuration[b]	$(1s)^4(1p_{3/2})^8(1p_{1/2})^2$	$(1s)^4(1p_{3/2})^8(1p_{1/2})^3$
Dominant final configuration	$(1s)^4(1p_{5/2})^8 1p_{1/2}$	$(1s)^4(1p_{3/2})^8(1p_{1/2})^2$
Target spin, parity	1^+	$\frac{1}{2}^-$
Final spin, parity	$\frac{1}{2}^-$	0^+
Incident energy (lab) (MeV)	14.1	14.8
r_{0n} (F)	1.25	1.25
r_{0d} (F)	1.4	1.4
a_n (F)	0.65	0.5
a_d (F)	0.7	0.7
V_n (MeV)	50.4	50.0
V_d (MeV)	66.0	76.0
W_n (MeV)	7.97	5.0
W_d (MeV)	7.0	10.0

[a] The proton potential had no imaginary part, had a form factor identical to that for the deuteron potential, and contained a derivative-type spin-orbit potential with a 6-MeV depth.

[b] I. Talmi and I. Unna [Ann. Rev. Nucl. Sci. **10**, 353 (1960)] find an admixture of $(1s)^4(1p_{3/2})^7(p_{1/2})^3$ in the ground state of N^{14}, but W. W. True [Phys. Rev. **30**, 1530 (1963)] finds a pure $(1s)^4(1p_{3/3})^8(1p_{1/2})^2$ configuration.

---

[18] M. H. Macfarlane and J. B. French, Rev. Mod. Phys. **32**, 567 (1960).

[19] E. F. Bennett, Phys. Rev. **122**, 595 (1958).

TABLE III. Reduced widths and spectroscopic factors.

Reaction	E_n (lab) (MeV)		Butler analysis			DWBA analysis	Extreme jj prediction	Intermediate-coupling prediction
		θ^2	θ_0^2	S	C^2S	C^2S	C^2S	(Ref. 30) C^2S
$N^{14}(n,d_0)C^{13}$	14.1	0.042[a]	0.046	0.92[a]	0.46[a]	1.02[a]	1	0.69
$N^{15}(n,d_0)C^{14}$	14.8	0.023[b]	0.041	0.55[b]	0.37[b]	1.11[b]	1	0.83

[a] ±10%. [b] ±15%.

Figure 4 also shows a DWBA fit to the data. The DWBA program was obtained from Smith[20] and has been applied with considerable success to a large number of (d,p) stripping reactions.[21,22] The optical potential employed in the program is shown in Table II along with the values for the parameters used in the present experiment. The parameters for the 14.1-MeV neutrons incident on N^{14} are identical, except for a slightly larger radius used in the present case, to the optical-model parameters determined by Lutz[23] for $n+N^{14}$ elastic scattering at 14 MeV. The elastic-scattering parameters for the outgoing $d+C^{13}$ channel were not available, so the form-factor parameters were taken to be the same as those found by Smith and Ivash in their analysis of light nuclei.[22] The other parameters used were those giving the best fit from a set of about 30 calculations (not an atuomatic search). Smith's program prints out the single-particle cross section (in units of 10^{-26} cm^2) times the stripping statistical factor $[(2J_{\text{final}}+1)/(2J_{\text{initial}}+1)]$. Thus, the reciprocity theorem may be used to yield an absolute value of the spectroscopic factor for the pickup reaction. The DWBA result for C^2S (at 25°) for pickup of a $j=\frac{1}{2}$ proton was 1.02 (Table III). The good agreement of this value with the jj prediction is certainly fortuitous in light of the remark made above concerning coupling in the region of the $1p$ shell,[18] and in view of the questionable ability of an optical-model analysis to yield absolute spectroscopic factors for transitions involving light nuclei.[22]

$N^{14}(n,t)C^{12}$ $(E_x=0)$

The angular distribution measured for this reaction is shown in Fig. 5. This is a $1^+\rightarrow 0^+$ transition, so the selection rules for angular momentum and parity allow only $l=0$, 2 for the value of the transferred orbital angular momentum. Also, the spin of the transferred neutron-proton pair must be in the triplet state to satisfy the selection rules. The result of Newns's plane-wave theory, simplified to the case where the neutron and proton are assumed to travel together, leads to a differential cross section proportional to

$$\exp(-K^2/4\beta^2)\sum_l |A(JlS)j_l(Qr_0)|^2,$$

where K is a function of the triton and neutron wave vectors $(=\frac{1}{3}\mathbf{k}_t-\mathbf{k}_n)$, β is the constant appearing in the triton Gaussian internal wave function, A is an amplitude, S is the neutron-proton spin, Q is the momentum transfer, and j_l is a spherical Bessel function.[24] The curve based on this expression with $\beta^{-1}=4\times10^{-13}$ cm,[25] $l=2$, and a radius of 6.4 F is shown in Fig. 5. Since the fit was quite good, no admixture of $l=0$ was added. Priest has studied the inverse mirror reaction $C^{12}(He^3,p)N^{14}$ $(E_x=0)$ at $E_{He^3}=13.9$ MeV.[26] If the simplest ideas of the double-stripping theory were applicable, then the He^3 could be considered a loosely bound deuteron-proton system subject to stripping in the same manner as single-nucleon stripping when the He^3 passes near the C^{12} nucleus. In that case one might expect, if Coulomb effects were not too important, that the ground-state angular distributions of the $C^{12}(He^3,p)N^{14}$ and $N^{14}(n,t)C^{12}$ reactions would be similar. It turn out that the angular distributions have almost exactly the same shape, and both are fitted well by a simple

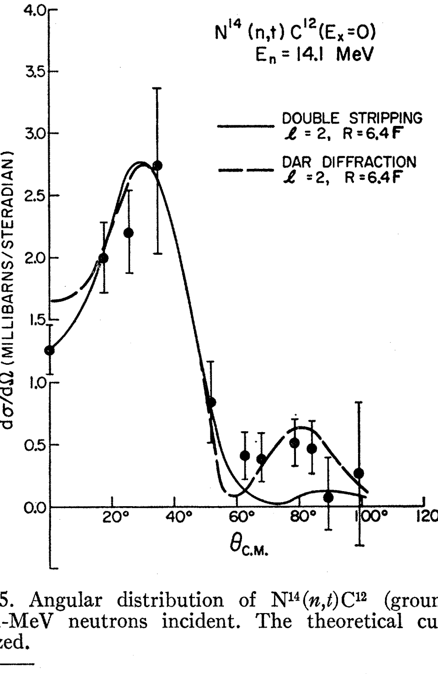


FIG. 5. Angular distribution of $N^{14}(n,t)C^{12}$ (ground state) for 14.1-MeV neutrons incident. The theoretical curves are normalized.

---

[20] W. R. Smith, University of Texas, 1962 (unpublished).

[21] W. R. Smith and E. V. Ivash, Phys. Rev. **128**, 1175 (1962).

[22] W. R. Smith and E. V. Ivash, Phys. Rev. **131**, 304 (1963).

[23] H. F. Lutz, J. B. Mason, and M. D. Karvelis, Nucl. Phys. **47**, 521 (1963).

[24] H. C. Newns, Proc. Phys. Soc. (London) **76**, 489 (1960).

[25] J. C. Gunn and J. Irving, Phil. Mag. **42**, 1353 (1951).

[26] J. R. Priest, D. J. Tondam, and E. Bleuler, Atomic Energy Commission Report No. TID 5700, 1960 (unpublished); Phys. Rev. **119**, 1295 (1960).

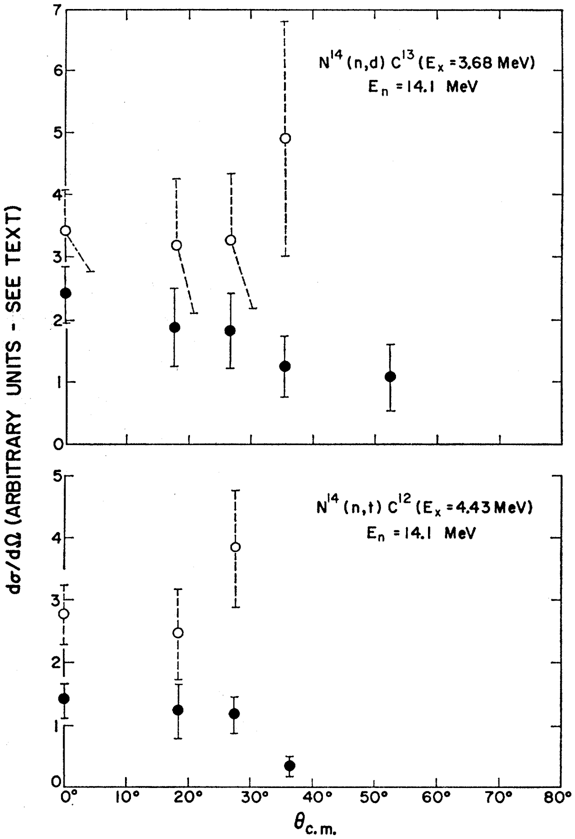


FIG. 6. Angular distributions of $N^{14}(n,d)C^{13}$ (second excited state) (top) and $N^{14}(n,t)C^{12}$ (first excited state) (bottom) for 14.1-MeV neutrons incident. The solid points contain no correction for effective target thickness, but the open points contain this correction. No reliable effective target-thickness calculation could be made for the largest angles where the energy cutoff was almost complete (see text).

plane-wave expression with $l=2$. If one accepts this as evidence for the correctness of the simplest interpretation of double stripping, it may be concluded that the reaction proceeds mainly by an $l=2$ transition. (The fact that the transferred neutron-proton system must have a triplet configuration in order to conserve parity for these reactions suggests the deuteron. This may be a partial explanation of the apparent success of the simple theory for the two cases.) This is in agreement with what is predicted from simple shell-model considerations. The model depicts the N^{14} ground state as two $(1p_{1/2})$ nucleons outside a C^{12} core, so that a transition between the N^{14} and C^{12} ground states transfers two units of orbital angular momentum.

The other curve shown in Fig. 5 was calculated using the diffraction theory of direct nuclear reactions due to Dar,[27] assuming $l=2$ and a radius of $R=6.4$ F. For the allowed values of $l=0$ and 2, the Dar result predicts angular distributions with $J_{l=0}{}^2$ and $(\frac{1}{4}J_{l=0}{}^2+\frac{3}{4}J_{l=2}{}^2)$ shapes, respectively, where the J's are cylindrical Bessel functions. (There is also a multiplicative form factor equal to $[1+(k_t/k_n)\cos\theta]^2$, and all quantities are expressed in the laboratory system.) Again, the data are quite well fitted with the assumption of a pure $l=2$ transition, and any significant admixture of the $l=0$ expression would make the fit worse. The diffraction analysis is therefore consistent with the double-stripping interpretation, as it suggests the same simple model of the N^{14} ground state as a deuteron coupled with relative orbital angular momentum $l=2$ to a C^{12} core.

$N^{14}(n,d)C^{13}$ ($E_x=3.68$ MeV)
$N^{14}(n,t)C^{12}$ ($E_x=4.43$ MeV)

The state at 4.43 MeV in C^{12} is isolated, but that at 3.68 MeV in C^{13} is between states at 3.09 and 3.85 MeV. Reactions proceeding to the 3.09- and 3.85-MeV levels are not expected to be important, however, as has been discussed and supported by experimental evidence in Ref. 5. Accordingly, transitions to these two states in C^{13} will not be considered further in the present paper.

The spin and parity of the 3.68-MeV state in C^{13} are $J^\pi=\frac{3}{2}^-$, and consequently $l=1, 3$ are the only values allowed for the (n,d) transition. Similarly, $l=0$, 2, 4 are allowed for the (n,t) transition. The experiment of Carlson,[4] as well as that of Zatzick and Maxson,[5] led to the assignment of pure $l=1$ transfer for the (n,d) case. Also, the intensity of the excited-state transition was found to be almost equal to that of the reaction leading to the ground state. This latter result is regarded as somewhat anomalous because it is in sharp contrast to the theoretical predictions,[18] and disagrees[18,19] with the experimental results obtained for the mirror reaction leading to the 3.51 MeV, $\frac{3}{2}^-$ state in N^{13}. (Both theory and the mirror experiment predict a yield to the $\frac{3}{2}^-$ state considerably smaller than the yield to the ground state.)

The Q values for these (n,d) and (n,t) transitions are such that the deuterons and tritons in question have similar energies, particularly after the energy absorbing effects of target thickness and anything else between the target and counters. It was hoped that the present experiment, for which a good particle-discrimination system was available, might resolve the confusion concerning the anomalously large excited-state deuteron yield by measuring both uncontaminated deuteron and triton spectra. The solid points in Fig. 6 show the angular distributions measured for these excited-state transitions. Unfortunately, the energies of the particles were so low that even at forward angles the particle groups were partially cut off. However, at all angles the excited-state triton group was the most seriously affected (see Table I). Thus, Fig. 6 indicates that the tritons may very well have been present in numbers sufficiently great to have led to misinterpretation in the earlier (n,d) experiments.

The ordinates of Fig. 6 are labeled in "arbitrary units," but the numbers are really the cross sections in

---

[27] A. Dar, Nucl. Phys. 55, 305 (1964).

mb/sr determined from the number of counts recorded. The solid points then are lower limits for the respective cross sections, since these points contain no correction for cutoff.

The open circles of Fig. 6 are the cross sections calculated using an effective target thickness determined by the maximum depth in the target from which the deuterons or tritons could be emitted and still deposit sufficient energy in the E detector. Although the dotted error bars (which are merely projections of the solid error bars) are large, the corrected points for the (n,d) case are in better agreement with expectations than the previous results[4,5] (see above). It is interesting to note that for a given angle the sum of the corrected cross sections for the (n,d) and (n,t) excited-state transitions is approximately equal to the (n,d) yield reported previously[4,5] (for which the d-t discrimination was poor).

$N^{15}(n,d)C^{14}$ $(E_x=0)$

The spin of N^{15} is $\frac{1}{2}^-$ so that only an $l=1$ transition is allowed on the basis of the conservation of angular momentum and parity. However, the result obtained with 14.1-MeV neutrons (Fig. 7) does not resemble a transition characterized by $l=1$. This is in contrast to the result of Chiba,[28] who studied the inverse reaction, $C^{14}(d,n)N^{15}$, and obtained a good $l=1$ fit to the forward peak as measured with incident deuterons of 3.53 MeV. If a direct-reaction mechanism were dominant throughout the energy range of interest, the (n,d) reaction at 14.1 MeV should also have the characteristic $l=1$ shape.

At a lower deuteron energy of 2.8 MeV, however, Chiba did not get a Butler type of distribution. Also Imhof *et al.*,[29] who studied the $C^{14}(d,n)$ reaction at several bombarding energies between 1.3 and 3.1 MeV, reported that none of the angular distributions resembled the Butler $l=1$ prediction. Thus, a compound mechanism is suggested. This is further emphasized by Chiba's excitation functions, which showed a number of resonances up to 3.1-MeV deuteron energy (13.1-MeV excitation energy in the N^{16} compound nucleus).

A 14.1-MeV neutron incident on N^{15} leads to a N^{16} excitation energy of 14.9 MeV, which is significantly above the highest resonance reported by Chiba. However, since this region of excitation in the N^{16} nucleus has not been very well investigated, the possibility exists that there is a resonance near 14.9 MeV in N^{16} causing a compound mechanism to dominate. Therefore, it was decided to measure an (n,d) angular distribution using the higher-energy neutrons (14.8 MeV) which are emitted at 0° from the $T(d,n)$ reaction. The results are shown in Fig. 8. These data have the direct-reaction shape, and the peak is fitted by an $l=1$ Butler curve. In addition, there is fair agreement with the $C^{14}(d,n)$ cross section at 3.53 MeV which predicts, via the reciprocity theorem, an (n,d) peak cross section of 1.8±0.7 mb/sr for 14.8-MeV neutrons incident on N^{15}.

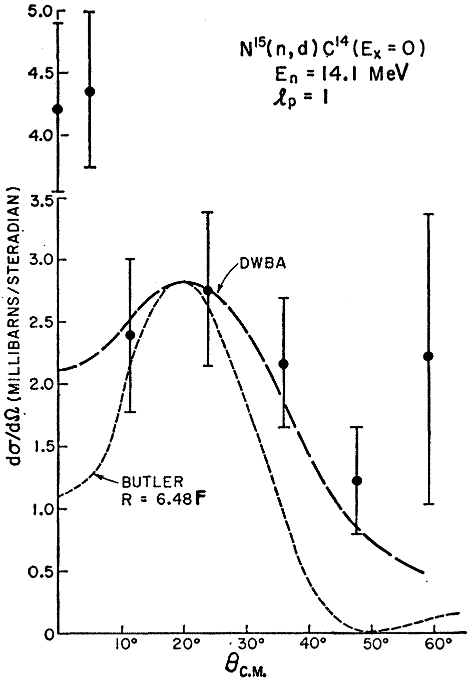


FIG. 7. Angular distribution of $N^{15}(n,d)C^{14}$ (ground state) for 14.1-MeV neutrons incident. The theoretical curves (normalized) are not intended as a fit to the data (see text).

The absolute reduced width θ^2 extracted from the Butler curve is 0.023±15%, which when divided by

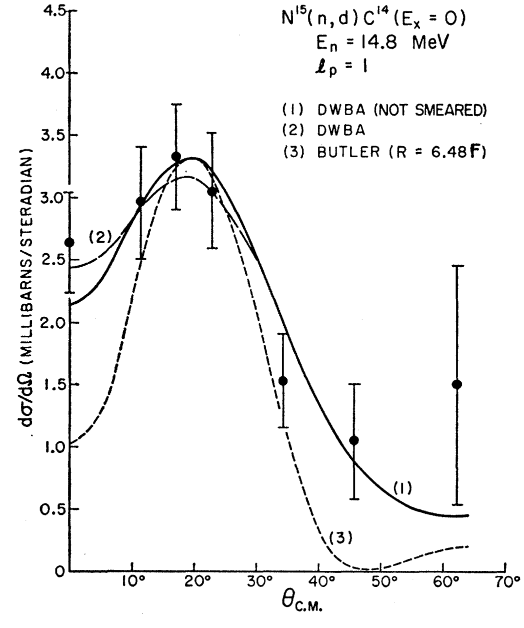


FIG. 8. Angular distribution of $N^{15}(n,d)C^{14}$ (ground state) for 14.8-MeV neutrons incident. The theoretical curves are normalized.

---

[28] Ren Chiba, Phys. Rev. **123**, 1316 (1961).

[29] W. L. Imhof, H. A. Grench, and R. G. Johnson, Nucl. Phys. **49**, 503 (1963).

the single-particle reduced width θ_0^2 (0.041 for this reaction) yields a spectroscopic factor $S=0.55\pm15\%$. The *jj* shell-model prediction of the spectroscopic factor for this reaction can be calculated most easily as C^2S by using the formalism without isotopic spin.[18] In this treatment the transition is between the proton configurations $(1s_{1/2})^2(1p_{3/2})^4(1p_{1/2})$ and $(1s_{1/2})^2(1p_{3/2})^4$, so that $C^2S=1$ (the number of equivalent $(1p_{1/2})$ protons involved). Since the isotopic spin coupling coefficient C is $\sqrt{\frac{2}{3}}$ for this transition, the theoretical value of S is 1.5. This case is similar to the $\mathrm{N}^{14}(n,d)\mathrm{C}^{13}$ $(E_x=0)$ reaction in that a large value (~1) of S is expected because both the dynamics ($l=1$) and the model (transfer of a p nucleon) favor the transition. The present experimental value of 0.55 for the $\mathrm{N}^{15}(n,d)$ reaction, as well as the limits on S of $0.5\leq S\leq1$ deduced by Macfarlane and French from other experimental evidence,[18] are somewhat below the pure *jj* coupling value of 1.5. Again, this is not surprising, since intermediate coupling is thought to be a more accurate description of the nuclear configurations in this region.

The solid curve in Fig. 8 shows the unsmeared DWBA curve (normalized) and the dashed curve shows the effect of smearing. (All curves reported in this paper have been smeared as discussed in Sec. II.) Since the elastic-scattering parameters for $n+\mathrm{N}^{15}$ and $d+\mathrm{C}^{14}$ were not available, the parameters used (Table II) were selected in a similar manner to those chosen for $d+\mathrm{C}^{13}$. The DWBA fit is clearly superior to the Butler fit. The DWBA value for C^2S (at 20°) is 1.11, but again, the agreement between this value and the *jj* prediction is probably fortuitous.

The two curves (Butler and DWBA) that fit the 14.8-MeV data were recalculated for a neutron energy of 14.1 MeV, and these curves are shown in Fig. 7. The fact that these direct-reaction curves change so little with the change in neutron energy, while the data change so drastically, is strong evidence that a compound process contributes significantly to the 14.1-MeV neutron results. A number of DWBA calculations (all with $l=1$) were performed in an attempt to fit these data. None of the calculated curves provided a fit, even though extreme values for the optical potentials were tried.

No particle groups of tritons or of deuterons leaving C^{14} in an excited state were detected in the present experiment.

IV. CONCLUSIONS

Except for the $\mathrm{N}^{15}(n,d)\mathrm{C}^{14}$ results at 14.1 MeV, all of the ground-state angular distributions were reproduced by one or more direct-reaction theories. However, it is not clear whether the success in explaining the $\mathrm{N}^{15}(n,d)\mathrm{C}^{14}$ results at 14.8-MeV neutron energy should be attributed to being in an off-resonance region in the compound system, or whether the 500-keV spread of this higher-energy neutron beam was effective in averaging over the compound resonances. Clearly there is a need for more investigation of the level structure of the N^{16} nucleus near 15 MeV of excitation energy.

It is interesting to compare the results for C^2S for the (n,d) ground-state transitions with theoretical spectroscopic factors calculated from realistic wave functions. The last column in Table III shows C^2S calculated from configuration—mixed wave functions derived from the $1p$-shell analysis of Cohen and Kurath.[30] As expected from the impurity of the more realistic configurations involved, these C^2S values are smaller than the pure *jj* values. If one makes the reasonable assumption that these calculated values of C^2S are correct, then the DWBA results for C^2S show that the DWBA treatment is able to predict the single-particle cross sections for the $\mathrm{N}^{14,15}(n,d)$ ground-state transitions to within about 30%.

The (n,t) results provided an illustration that this type of reaction at 14 MeV can successfully be interpreted as a direct two-nucleon transfer process. Although the particular theories used in the present instance were rather crude, the fits obtained were good enough to encourage further (n,t) studies. Unfortunately, most (n,t) reactions have Q values considerably more negative than that for $\mathrm{N}^{14}(n,t)$. The availability of accelerators producing deuterons (and tritons) in the 3–7-MeV range make sources of neutrons with energies greater than 14 MeV generally available, however, so that this should not be too much of a problem. Also, now that triton elastic-scattering parameters are becoming available,[31] it will be interesting to see what success future DWBA codes will have in more sophisticated analyses of (n,t) reactions.

The results obtained here for the $\mathrm{N}^{14}(n,d)$ and (n,t) reactions leaving the residual nuclei in the excited states (Fig. 6) were not conclusive, but did indicate that both excited-state transitions have significant yields. For better resolution of the question of the anomalously large cross section for the transition to the 3.68-MeV level of C^{13}, additional work with thinner dE/dx counters and/or a higher neutron energy would be useful.[32]

ACKNOWLEDGMENTS

The authors wish to thank Dr. Richard D. Murphy and Dr. Robert R. Wagner for their assistance in the laboratory. We are indebted to Dr. J. Mailen Kootsey for the pulse multiplier and aperture-function computer program, and to Dr. William R. Smith and Professor Eugene V. Ivash for the DWBA program.

---

[30] D. Kurath (private communication) has provided spectroscopic factors for the $\mathrm{N}^{14,15}(n,d)\mathrm{C}^{13,14}$ reactions. These calculations were based on the intermediate-coupling p-shell analysis of S. Cohen and D. Kurath, Nucl. Phys. **73**, 1 (1965). [The calculations showed that only $(j=\frac{1}{2})$ pickup was important for these ground-state transitions.]

[31] R. N. Glover and A. D. W. Jones, Nucl. Phys. **81**, 268 (1966).

[32] After the present paper was submitted for publication, we became aware of some recent results obtained with thinner dE/dx counters [D. Rendić, Nucl. Phys. **A91**, 604 (1967); and G. Paić (private communication)]. This work confirms our results for the $\mathrm{N}^{14}(n,d)$ and (n,t) transitions.