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Mechanism of $^{14}\text{N}(t,p)$ to the ground state quadruplet in ^{16}N

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Complete angular distributions (8° – 168°) have been measured for the $^{14}\text{N}(t,p)^{16}\text{N}$ reaction, at a bombarding energy of 15 MeV, leading to the lowest four levels of ^{16}N . Results have been analyzed using distorted-wave Born approximation and microscopic wave functions. The approximate magnitude of the compound-nucleus component has been extracted.

[NUCLEAR REACTION $^{14}\text{N}(t,p)$, $E=15$ MeV; ^{16}N levels, deduced reaction mechanism and tested shell-model wave functions. DWBA analysis.]

An earlier distorted-wave Born-approximation (DWBA) analysis¹ of the $^{14}\text{N}(t,p)^{16}\text{N}$ reaction² at a bombarding energy of 12 MeV gave somewhat unsatisfactory results for the low-lying quadruplet of states (2^- , 0^- , 3^- , 1^-) when wave functions of Zücker, Buck, and McGrory (ZBM) (Ref. 3) were used in the calculation. In particular, shapes of the angular distributions were not well fitted, and extracted overall normalization factors among the four states varied by a factor of 3. In a new investigation of this reaction, the present results go beyond the earlier work in a number of ways:

- (1) A somewhat higher bombarding energy—15 MeV rather than 12.
- (2) Measurement of absolute cross sections (no absolute cross sections were available in the earlier data).
- (3) Complete (8° – 168°) angular distributions in order to investigate possible presence of compound-nucleus contributions to the cross sections.
- (4) The use of more than one set of wave functions in the analysis.

The experiment made use of a 15-MeV t beam from the University of Pennsylvania FN tandem and a gas target. Protons were momentum analyzed in a multiangle spectrograph and detected in nuclear emulsion plates. Data were recorded in 7.5° intervals from 7.5° to 165° . The present report concerns only the lowest four states, whose angular distributions are displayed in Fig. 1.

The curves in Fig. 1 were computed with the microscopic two-nucleon transfer option of the code DWUCK,⁴ using ZBM wave functions. The solid curves were obtained using the same optical-model parameters as used in Ref. 1. The dashed curves were calculated with the same triton potential, but a different proton potential. All potential parameters are listed in Table I. The overall normalization factors N obtained by normalizing the curves to the data as shown, are given

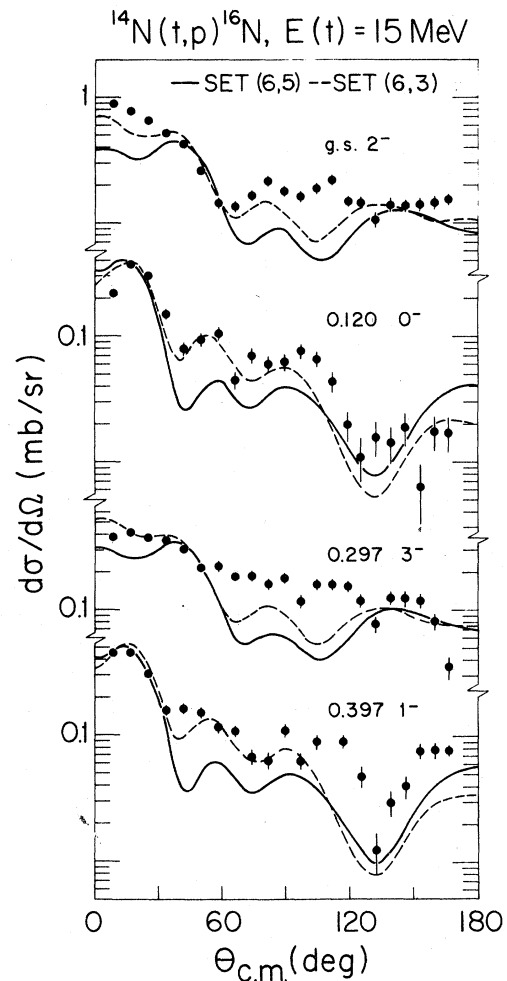


FIG. 1. Angular distributions of the $^{14}\text{N}(t,p)^{16}\text{N}$ reaction leading to the g.s. quadruplet in ^{16}N . Curves are results of DWBA calculations with the optical-model potentials indicated [solid curves, potential combination (6, 5); dashed set (6, 3)—potentials listed in Table I], and amplitudes from ZBM wave functions (Table III). Resulting normalization factors are listed in Table II.

TABLE I. Optical-model parameters used in DWBA analysis of $^{14}\text{N}(t,p)^{16}\text{N}$. Strengths are in MeV, lengths in fm.

Channel	Label	V	W	$W' = 4W_D$	V_{so}	$r_0 = r_{\text{so}}$	$a = a_{\text{so}}$	r'_0	a'	r_{0c}
t	6	130	18.9	0	0	1.29	0.58	1.37	0.96	1.29
p	5	60	0	34.2	5.5	1.13	0.57	1.13	0.50	1.13
	3	$V(E)^a$	0	54.0	7.5	1.25	0.65	1.25	0.47	1.25
Bound state		$\lambda = 25$	1.26	0.60

^a $V(E) = 53.3 - 0.55E + 0.4Z/A^{1/3} + 27(N-Z)/A$. See F. G. Perey, Phys. Rev. 131, 745 (1963).

in Table II. The quantity, N , is defined by the expression

$$\sigma_{\text{exp}}(\theta) = N \frac{2J_f + 1}{2J_i + 1} \sum_{J_x} \frac{\sigma_{\text{DW}}(\theta)}{2J_x + 1},$$

where J_i , J_x , and J_f are the initial, transferred, and final total angular momenta, respectively, and $\sigma_{\text{DW}}(\theta)$ is the quantity computed in DWUCK.

A number of points are apparent from inspection of Fig. 1 and Table II. First, the calculations underpredict the cross section for all four states at most angles beyond 60° perhaps implying a compound-nucleus (CN) reaction component. The fact that the back-angle cross section is larger for states of larger J_f is consistent with this idea, since σ_{CN} should be roughly proportional to $2J_f + 1$. Second, even though the dashed curves fit the data somewhat better than do the solid curves, the ground state (g.s.) angular distribution in both cases is poorly fitted. It was noted in Ref. 1 that the fit could be markedly improved by the inclusion of an $L = 1$ component, which is allowed by the macroscopic selection rules, but predicted to be very small with the ZBM wave functions. The same is true here. We return to this point below. Third, the values of N still fluctuate, though not as badly as in Ref. 1. Comparing these values of N with those normally encountered in (t, p) reactions^{5,6,7} on nearby nuclei, in which potential combination (6, 5) was used, we note that the 1^- is weaker than expected by about a factor of 2 and the other three states have about the right strength. In an attempt to estimate the compound-nucleus

TABLE II. Normalization factors obtained for $^{14}\text{N}(t,p)^{16}\text{N}$. Numbers in parentheses denote potential combinations. ZBM denotes wave functions from Ref. 2, $^{15}\text{N} + sd$ wave functions described in the text.

E_x	J^π	15 MeV			
		12 MeV ^a (6,5)ZBM	ZBM (6,3)	(6,5)	$^{15}\text{N} + sd$ (6,5)
0.0	2^-	1.56	490	299	237
0.120	0^-	0.84	390	235	164
0.297	3^-	1.02	450	280	273
0.397	1^-	0.58	270	153	155

^a Reference 1 (arbitrary units).

component, we have integrated the experimental angular distributions to obtain values of σ_{tot} for the four states. We plot in Fig. 2 this quantity divided by $2J_f + 1$ vs $\sigma_{\text{dir}}/(2J_f + 1)$, where

$$\sigma_{\text{dir}} = \frac{2J_f + 1}{2J_i + 1} \sum_{J_x} \frac{\int \sigma_{\text{DW}}(\theta) d\Omega}{2J_x + 1}.$$

If the direct and CN cross sections are incoherent, and if the CN cross section is proportional to $2J_f + 1$, we expect

$$\sigma_{\text{tot}} = \sigma_c(2J_f + 1) + N\sigma_{\text{dir}},$$

so that a plot of $\sigma_{\text{tot}}/(2J_f + 1)$ vs $\sigma_{\text{dir}}/(2J_f + 1)$ should produce a straight line of slope N and y intercept σ_c . With the ZBM wave functions, the points deviate quite a bit from a straight line (top of Fig. 2). Nevertheless, the best fit straight line gives a slope of $N = 300 \pm 30$ and an intercept of $\sigma_c = 110 \pm 15 \mu\text{b}$. A similar analysis of $^{14}\text{N}(^3\text{He}, p)$ data at the same bombarding energy and with ZBM wave functions gave⁸ $\sigma_c = 86 \pm 15 \mu\text{b}$ and (after correcting for a factor $D_{01}^2 = 0.72$) $N = 277 \pm 42$. Thus the two analyses are consistent and suggest the

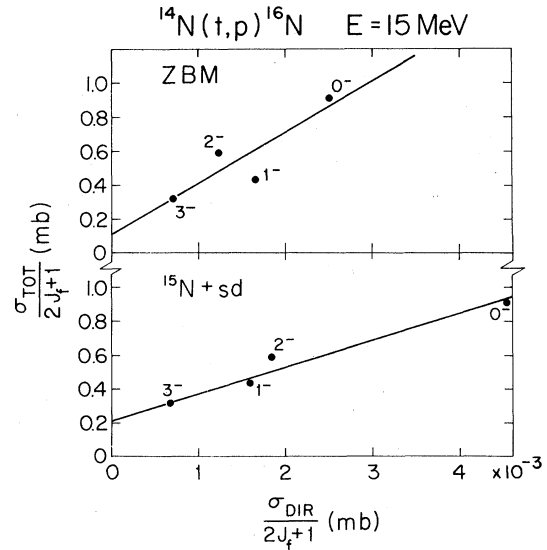


FIG. 2. Plot of measured angle-integrated cross sections divided by $2J_f + 1$ vs. calculated ones using potential combination (6, 5) and ZBM amplitudes (top) and $^{15}\text{N} + sd$ amplitudes (bottom).

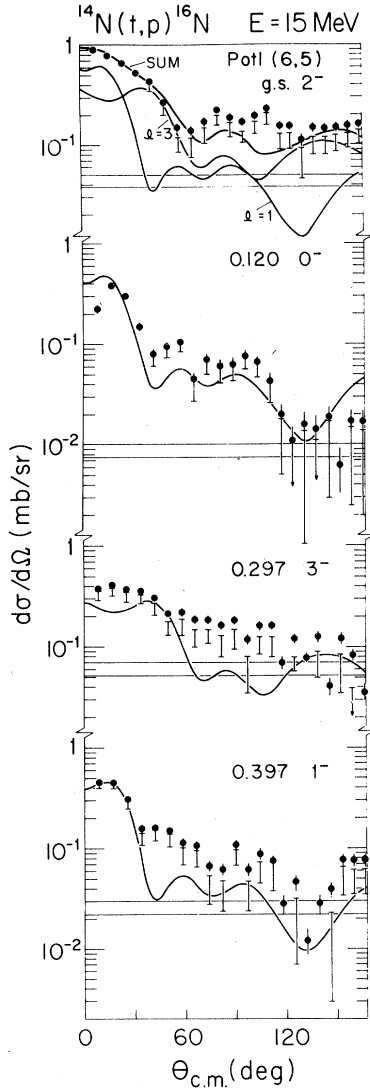


FIG. 3. Data points are the same as Fig. 1. The range of zeroth-order estimates of σ_{CN} are indicated by horizontal lines. When these have been subtracted from the data angle-by-angle, the corrected data points are indicated by vertical bars. Note that the forward-angle cross sections are barely affected. The result was then fitted with arbitrary admixtures of the allowed L values.

presence of a small CN component. We have plotted in Fig. 3 as horizontal lines the quantity $(\sigma_0/4\pi)(2J_f+1)$. This is the value $\sigma_{\text{CN}}(\theta)$ would have if it were isotropic. We note with this choice that (1) σ_{CN} is comparable to or only slightly less than the measured back-angle cross section, and (2) the forward-angle fits and resulting normalization factors are little affected if this value of $\sigma_{\text{CN}}(\theta)$ is subtracted from the data. In particular, the g.s. angular distribution still requires an $L=1$ component. Isotropy is a poor assumption for

TABLE III. Two-neutron transfer amplitudes for $^{14}\text{N} \rightarrow ^{16}\text{N}$.

J^π	$J_x=L$	Configuration	Amplitude	
			ZBM	$^{15}\text{N} + sd$
2^-	3	$1p_{1/2} \quad 1d_{5/2}$	-0.960	-1.0534
	3	$1p_{3/2} \quad 1d_{5/2}$	0	+0.1002
0^-	1	$1p_{3/2} \quad 1d_{5/2}$	0	+0.0985
	1	$1p_{1/2} \quad 2s_{1/2}$	1.07	-1.1943
3^-	1	$1p_{3/2} \quad 2s_{1/2}$	0	+0.1798
	3	$1p_{1/2} \quad 1d_{5/2}$	0.718	-0.7963
1^-	3	$1p_{3/2} \quad 1d_{5/2}$	0	-0.0733
	1	$1p_{1/2} \quad 2s_{1/2}$	0.865	-0.9751
	1	$1p_{3/2} \quad 2s_{1/2}$	0	-0.0733

$\sigma_{\text{CN}}(\theta)$, but these two main conclusions would not be affected by a more realistic treatment of σ_{CN} . We thus conclude that the poor fit to the ground-state angular distribution and the smaller value of N for the 1^- state (than for the other states)

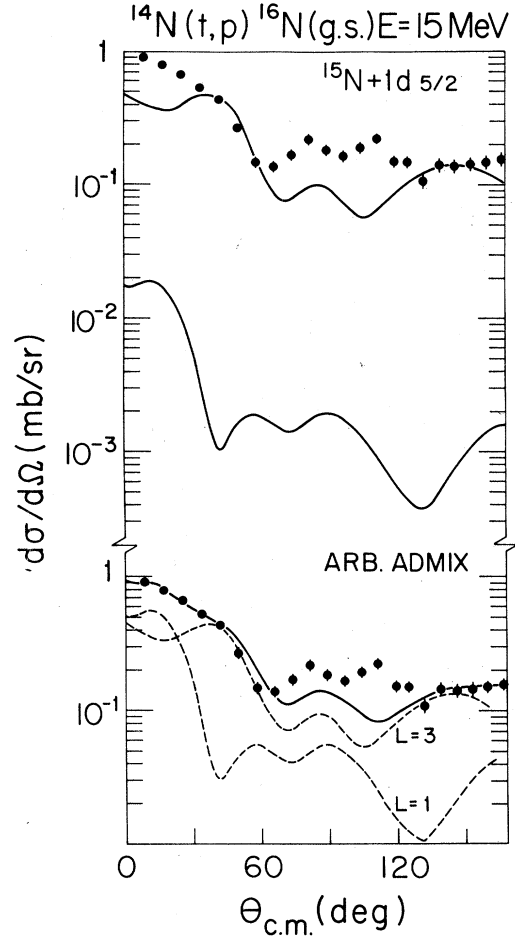


FIG. 4. Angular distribution for the 2^- ground state and DWBA curves from potentials (6,5), using $^{15}\text{N} + sd$ amplitudes (top) and arbitrary L admixtures (bottom).

are not caused by CN effects.

We next investigate the dependence of N on the exact nature of the wave functions assumed. Since the g.s. quadruplet might be better described as pure one-particle one-hole ($1p-1h$) states, we have chosen to calculate angular distributions assuming the states are pure $2s_{1/2}$ or $1d_{5/2}$ single particles coupled to the ^{15}N (g.s.). We use the Cohen-Kurath⁹ wave functions for ^{14}N and ^{15}N , viz., amplitudes for $^{14}\text{N} \rightarrow ^{15}\text{N}$ of $A_{p_{1/2}} = -0.3601\sqrt{11}$ and $A_{p_{3/2}} = 0.0542\sqrt{11}$ for $p_{1/2}$ and $p_{3/2}$, respectively. The $^{14}\text{N} \rightarrow ^{16}\text{N}$ amplitudes for a given L transfer are then just

$$A_L = W(l_1 j_1 l_2 j_2; \frac{1}{2} L) A_{l_1 j_1},$$

where subscript 1 refers to the p shell and subscript 2 to the sd shell, and W is a Racah coefficient. The resulting amplitudes are listed in Table III. The principal changes are that the 1^- state can now be reached by an additional component, $1p_{3/2}2s_{1/2}$, and the 2^- g.s. now has an $L=1$ component, viz., $1p_{3/2}1d_{5/2}$.

The DWBA shapes for given L are barely affected by these changes, but the normalization factors, listed in Table II, are. Now the N values for the 0^- and 1^- states are roughly equal, as are those for the 2^- and 3^- states, but the latter are about twice the former. Furthermore, though the g.s. now has an $L=1$ component, the $L=1$ contribution is still too small by about a factor of 30 (Fig. 4).

The plot of σ_{tot} vs σ_{dir} (bottom of Fig. 2) is also changed. With the $^{15}\text{N} + sd$ wave functions, the points lie much closer to a straight line, but now $N=160$ and $\sigma_c=210 \mu\text{b}$. If we take this analysis at face value, it would suggest that with this potential combination we should expect $N \approx 160$, rather than 300, and that a large fraction of the cross section for the 2^- and 3^- states (35% and 66%, respectively) comes from compound-nucleus processes. Or, alternatively, the states of ^{16}N are not very pure single-particle states coupled to ^{15}N .

Unfortunately, the number of nuclei in which one can reach negative-parity states via (t, p) with transfers of the type $(1p)(sd)$ are small. We note that in ^{14}C , there exist 1^- and 3^- states (at 6.09 and 6.72 MeV, respectively) that are thought to be reasonably $1p_{1/2}2s_{1/2}$ and $1p_{1/2}1d_{5/2}$ configurations built on the ^{12}C ground state. In an analysis⁷ of the $^{12}\text{C}(t, p)^{14}\text{C}$ reaction, using potentials (6, 5) the values of N extracted were 200 for the 1^- and 260 for the 3^- . It would appear that even when wave functions are simple and reasonably well known, one cannot compute (t, p) cross sections to better than 50%.

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