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Distorted-Wave Analysis of the $^{13}C(^3He, d)$ Reaction Leading to Unbound Levels of ^{14}N†

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Distorted-wave calculations are compared with data from the $^{13}C(^3He, d)^{14}N$ reaction leading to proton-unbound levels at $E_x = 7.966$ MeV ($2^{\pm}$, $T=0$), 8.489 MeV (4^-, $T=0$), 8.617 MeV (0^+, $T=1$), and 8.907 MeV (3^-, $T=1$). Results show appreciable nondirect components for population of the 4^- and 0^+ states. The 7.966-MeV state is suggested to have positive parity, and a definite prediction is made for its width. The spectroscopic factor for the 3^-, $T=1$ state approaches unity, in good agreement with theoretical calculations.

I. INTRODUCTION

A large quantity of information is available[1] for the few lowest particle-unstable states of ^{14}N. Most of the states within 3 MeV of the proton threshold (which occurs at $E_x = 7.550$ MeV) have unique spin, parity, and isospin assignments.[1] However, there exists a discrepancy for the lowest unbound level (at $E_x = 7.966$ MeV). This state is assigned $T=0$, since it is seen in the $^{12}C(\alpha, d)$-^{14}N reaction.[2] From a $^{13}C(p, \gamma)$ study,[3] this state is suggested to have $J^\pi = 2^-$. Those data rigorously eliminate $J=0$ and $J \geq 3$. Of the remaining $1^{\pm}$, $2^{\pm}$ possibilities, the 2^- assignment is consistent with but not required by the data. Systematics of angular distributions from a recent study[4] of the $^{13}C(^3He, d)^{14}N$ reaction suggest positive parity for the 7.966-MeV state. At the time of that study,[4] distorted-wave Born-approximation (DWBA) analysis for stripping to unbound states was not available; hence, unambiguous l values and spectroscopic factors could not be extracted for the unbound levels.

In the present work, distorted-wave angular distributions were calculated using a method recently developed for stripping to unbound states.[5,6] The main emphasis is on the state at 7.966 MeV, whose parity (and perhaps spin) is uncertain. However, results are also presented for the three other states for which angular distributions were extracted.[4,7] These are the levels at $E_x = 8.489$, 8.617, and 8.907 MeV. (The remaining unbound states listed in Ref. 7 were not separated from impurity peaks at a sufficient number of angles to enable angular distributions to be extracted.) The previously available information for these states is summarized in Table I.

II. ANALYSIS

Form factors for the unbound states were calculated as resonant eigenfunctions of a real Woods-Saxon potential, using the code ABACUS.[8] The depth of the well was adjusted separately for each state to reproduce the corresponding separation energy of the $^{13}C + p$ system. The parameters of the $^{13}C + p$ potential are contained in Table II along with the optical-model parameters used in the entrance and exit channels. The parameters of the entrance and exit channels are the same as those used in the DWBA calculations for the ^{13}C-$(^3He, d)$ transitions[7] to the bound states of ^{14}N. The

TABLE I. Previously available information (Ref. 1) on levels discussed herein.

E_p (c.m.) (MeV)	E_x (MeV)	Q (MeV)	J^π, T	Γ_{total} (keV)
0.416	7.966	−5.910	2^a, 0	<0.37
0.939	8.489	−6.433	4^-, 0	≤0.2
1.067	8.617	−6.561	0^+, 1	7 ±1
1.357	8.907	−6.851	3^-, 1	16 ±2

[a] Assigned negative parity by Ref. 3; however, positive parity was suggested by Ref. 4.

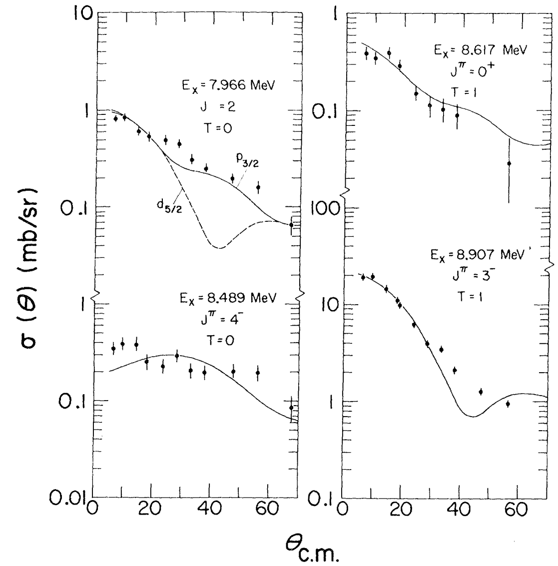

FIG. 1. Deuteron angular distributions for ^{13}C(^{3}He,d) transitions to the 7.966-, 8.489-, 8.617-, and 8.907-MeV levels in ^{14}N. The curves are the results of DWBA calculations. The values of l and j used in the calculations are listed in Table III. For the 7.966-MeV level the solid and broken curves correspond to proton transfer to the $1p_{3/2}$ and $1d_{5/2}$ configurations, respectively. The absolute experimental cross sections have been reduced by 25% to make these spectroscopic factors consistent with those of Ref. 7 (see text).

present calculations were performed in the local zero-range approximation using a specially modified[5,6] version of Tamura's code DWMAIN.[9]

In Fig. 1 the calculated angular distributions are compared with the data. The uncertainty in absolute cross section is estimated in Ref. 7 to be ±25%. In fact, in that work, the extracted absolute spectroscopic factors were renormalized by reducing them by 25% to bring them into closer agreement with theoretical predictions. In the present work, we have reduced the absolute cross sections of Ref. 7 by 25% so that our spectroscopic factors have the same normalization as those of Ref. 7. The values of l, the transferred orbital angular momentum, and j, the total transferred angular momentum, for each calculation are listed in Table III. Predictions for both $l=1$ and $l=2$ (corresponding, respectively, to positive- and negative-parity final states in ^{14}N) are shown for the transition to the 7.966-MeV state and are discussed in Sec. III.

III. RESULTS AND CONCLUSIONS

The proton widths Γ_p, which are the quantities extracted in the unbound DWBA analysis,[6] are presented in Table III for the four levels of interest. Also shown are the proton single-particle widths Γ_{sp} calculated with the code ABACUS[8] using the ^{13}C $+p$ potential parameters listed in Table II. The spectroscopic strengths listed were calculated under the assumption $\Gamma_p/\Gamma_{\text{sp}} \approx C^2S$. This assumption is known to be not strictly correct, but has been used in the absence of a better model to extract S from Γ_p. It is certainly expected to be accurate to better than a factor of 2. The square of the isospin Clebsch-Gordan coefficient C^2 is $\frac{1}{2}$ for (^{3}He,d) transitions to both $T=0$ and $T=1$ final states in ^{14}N.

For states with an extracted value of Γ_p which is large compared to typical γ widths, one would expect to have $\Gamma_p \approx \Gamma_{\text{total}}$, since no other particle decay channel is open for these four states. Each of the four levels is discussed, in turn, below.

8.907-MeV state. This state is known to have $J^\pi = 3^-$, $T=1$ and presumably has the dominant configuration $[1p_{1/2} \times 1d_{5/2}]_{3^-, T=1}$. The state at $E_x = 5.83$ in ^{14}N is thought to be the 3^-, $T=0$ member of this configuration. The distorted-wave calculation for $d_{5/2}$ transfer gives a reasonably good account of the data for the 8.907-MeV state. The extracted proton width $\Gamma_p = 12.1$ keV agrees reasonably well

TABLE II. Optical-model parameters used in the DWBA calculations.

Channel	V_0 (MeV)	W (MeV)	$W' = 4W_D$ (MeV)	$r_0 = r_{\text{so}}$ (F)	$a = a_{\text{so}}$ (F)	r_C (F)	r_0' (F)	a' (F)	V_{so} (MeV)
^{13}C + ^{3}He	158	6.75	0.0	0.93	0.81	1.40	2.25	0.65	6.0
^{14}N + d	86.3	0.0	39.7	1.105	0.9385	1.30	1.608	0.598	0.0
^{13}C + p	a	···	···	1.260	0.60	1.26	···	···	6.0

[a] The ^{13}C $+p$ well depths were adjusted to give the proton an unbinding energy of $B = -(5.494 + Q)$.

with the measured total width, $\Gamma_{total} = 16 \pm 2$ keV. (If the absolute cross sections of Ref. 7 had not been renormalized this width would have been $\Gamma_p = 16.1$ keV, in excellent agreement with the experimental total width.) The ratio of Γ_p to Γ_{sp} leads to an approximate spectroscopic factor $S \approx 2\Gamma_p/\Gamma_{sp} = 0.72$. Considering the difficulties in extracting S from Γ_p, this value is in good agreement with the theoretical value[10] of 0.96. This extracted value of $S \approx 0.72$ for the 3^-, $T=1$ state is larger than the value of $S = 0.55$ obtained[7] for the 3^-, $T=0$ state at $E_x = 5.83$ MeV. This, again, is in agreement with theoretical expectations. Sebe[10] predicts $S = 0.82$ for the 3^-, $T=0$ state, compared with $S = 0.96$ for $T=1$. Thus the *relative* spectroscopic factors for these two 3^- states agree with the theoretical predictions to better than 10%. If we had used the unrenormalized absolute cross section of Ref. 7, the ***absolute*** spectroscopic factors would have agreed with the theoretical values to within 5%.

8.617-MeV state. This state is known to have $J^{\pi} = 0^+$, $T=1$, and hence can be reached from ^{13}C only by $p_{1/2}$ transfer or by some nondirect mechanism. The cross section leading to this state is the smallest of any state observed in the $(^{3}He, d)$ reaction below 9 MeV. Thus, it might be expected that the angular distribution for this state could contain an appreciable nondirect component. It can be seen from Fig. 1 that the DWBA calculation for $p_{1/2}$ transfer gives a reasonable fit to the shape of the angular distribution. However, the extracted proton width, $\Gamma_p = 18$ keV, is more than a factor of 2 larger than the measured total width, $\Gamma_{total} = 7 \pm 1$ keV. This discrepancy is larger than expected in such analyses, but is in the right direction to be accounted for by a nondirect component in the angular distribution. For this state, the extracted Γ_p and the resulting C^2S are indicated as representing upper limits.

8.489-MeV state. Since this state has $J^{\pi} = 4^-$, it can be reached in the $^{13}C(^{3}He, d)$ reaction only by g-wave transfer or by a nondirect process. Of course, there is not expected to be any appreciable g-wave strength this low in ^{14}N. The angular distribution for this state is seen from Fig. 1 to be a very slowly varying function of angle. Furthermore, the predicted angular distribution for $g_{9/2}$ transfer does not agree with the forward angles of the experimental angular distribution for this weak transition [only two states below $E_x = 9$ MeV have smaller cross sections in the $(^{3}He, d)$ reaction]. Since nondirect components are very likely present, the values of Γ_p and C^2S given in Table III for this level merely represent upper limits. However, the extracted upper limit for the proton width, $\Gamma_p \leq 0.1$ eV, though much larger than the known[1] γ width of $\Gamma_\gamma = 5.6 \pm 2.0 \times 10^{-3}$ eV, is still well below the known limit on the total width[1] of this state, $\Gamma_{total} \leq 0.2$ keV.

TABLE III. Results of DWBA analysis.

E_x (MeV)	$J^{\pi}; T$	l	j	Γ_p (keV)	Γ_{sp}[a] (keV)	C^2S
7.966	$2^+, 0$	1	$\frac{3}{2}$	0.14	4.5	0.031
	$2^-, 0$	2	$\frac{5}{2}$	0.0033	0.175	0.019
8.489	$4^-, 0$	4	$\frac{9}{2}$	$<9.9 \times 10^{-5}$	~0.0026	<0.034
8.617	$0^+, 1$	1	$\frac{1}{2}$	<18.	152.	<0.12
8.907	$3^-, 1$	2	$\frac{5}{2}$	12.1	34.	0.36

[a] Calculated by the code ABACUS using parameters given in Table II for $^{13}C + p$.

7.966-MeV state. As discussed in the Introduction, this state has been suggested to have $J = 2$, with negative parity favored.[3] Previous studies of the $^{13}C(d, n)^{14}N$ reaction[11] at $E_d = 6$ MeV had nothing to say about the parity of this state, since the (d, n) reaction could not distinguish between $l=1$ and $l=2$ in this region of excitation. In addition, in those studies the 7.966-MeV state was covered by an impurity at several angles. From Fig. 1, it can be seen that the agreement between the calculated and experimental $(^{3}He, d)$ angular distributions is better for an $l=1$ transfer (corresponding to positive parity for this level) than for $l=2$. However, the comparison of *shapes* is not completely convincing. Comparison of the *magnitudes* of the experimental and theoretical cross sections leads to very definite predictions for the two different parities. Both the extracted proton widths for $l=1$ ($\Gamma_p = 0.14$ keV) and for $l=2$ ($\Gamma_p = 3.3$ eV) are within the known limit on the total width ($\Gamma_{total} < 0.37$ keV). But a more sensitive measurement of Γ_{total} should be capable of determining the parity. For example, a measurement of $\Gamma_{total} \ll 0.1$ keV would rule out positive parity, whereas a value of $\Gamma_{total} \approx 0.1$ keV would be strong evidence for positive parity. We would like to see such a measurement of Γ_{total} carried out for this state.

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Neutron Transfer to the Ground State of ^{14}C in the ^{13}C(^{14}N, ^{13}N)^{14}C Reaction*

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Thick targets of ^{13}C (91.7%) were bombarded with ^{14}N ions accelerated in the Oak Ridge tandem Van de Graaff, and the cross section for the neutron-transfer reaction ^{13}C(^{14}N, ^{13}N)^{14}C was measured from 12.5 to 20.5 MeV. The cross section measured in this energy range is due predominantly to transfer that proceed to the ^{14}C ground state, since the threshold for the reaction to populate the 6.09-MeV first excited state is 17.6 MeV. The measured excitation function was then compared with cross sections calculated from the recent distorted-wave Born-approximation (DWBA) treatment of Schmittroth, Tobocman, and Golestaneh. It was possible to find an optical potential for which the DWBA matched the observed excitation function above 14-MeV (lab) incident energy. From this fit the spectroscopic factor for the ^{14}C ground state was determined. The excitation function for the compound-nucleus reaction ^{13}C(^{14}N, $2p$)^{25}Na was also measured for ^{14}N incident energies from 13.5 to 20.5 MeV.

I. INTRODUCTION

The main motivation for the study of heavy-ion-induced transfer reactions has been the possibility that such investigations could be used to determine single-particle reduced widths and nuclear spectroscopic factors. A quantitative description of the transfer of neutrons between heavy ions for energies below the Coulomb barrier has been formulated by Breit and Ebel[1] specifically for the reaction ^{14}N(^{14}N, ^{13}N)^{15}N. Investigators[2,3] have used the theory to derive neutron reduced widths by measuring the total cross section for the reaction ^{14}N(^{14}N, ^{13}N)^{15}N as a function of energy, and by assuming that the reduced widths in ^{14}N and ^{15}N are equal. Good agreement was found[2,3] between the reduced widths extracted in this manner and values derived from shell-model calculations, and from (d,p) and (p,d) experiments on ^{14}N. Surprising success has also been attained in the extraction of the neutron reduced width in ^{11}B when the theory was applied[3] to cross-section measurements for the reaction ^{10}B(^{14}N, ^{13}N)^{11}B. The derived reduced width for ^{11}B agreed well with a shell-model calculation that assumed the ^{11}B ground state to be ^{10}B $+ 1p_{3/2}$ neutron. This agreement may have been largely coincidental or may have been observed because the neutron states involved in the ^{14}N and ^{10}B reactions are fairly similar.

The Coulomb-wave Born-approximation (CWBA) treatment has been proposed as an alternative to the tunneling theory.[4,5] When the CWBA treatment was applied to the ^{14}N(^{14}N, ^{13}N)^{15}N reaction, it was found to give results in agreement with those of the tunneling theory. The validity of the CWBA treatment, however, is not restricted to