Study of ^{14}N by Several Transfer Reactions*

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Nitrogen-14 has been studied by magnetic analysis of particles from the reactions ^{13}C(^{3}He, d)^{14}N, ^{12}C(^{3}He, p)^{14}N, ^{16}O(d, α)^{14}N, and ^{15}N(^{3}He, α)^{14}N. Measured angular distributions and intensities are consistent with present spin, parity, and isospin assignments. Doublets were observed at 8.97 and 8.99 MeV, and at 10.06 and 10.10 MeV. Evidence is presented that the 7.97-MeV state is not negative-parity. Strong evidence suggests the 6.21- and 6.44-MeV states may be considered to arise by excitation of two particles to higher shell-model orbitals. Other qualitative configurational assignments are also made.

I. INTRODUCTION

CONSIDERABLE information about the unbound states of ^{14}N has been obtained from the study of the resonances in the ^{13}C(p, p) excitation curve,[1–3] and analysis of γ-ray decay rates and branching ratios in ^{14}N has also been very useful.[4] In fact, these two sources of information have been used to assign spins and parities with varying degrees of reliability to almost every state up to 13-MeV excitation. Nevertheless, much can still be learned by studies of ^{14}N in other ways.

Table I lists four different reactions and their ground-state Q values leading to ^{14}N. The ^{13}C(^{3}He, d)^{14}N reaction has already been used to study the bound states in some detail.[5] It was found to be a direct reaction proceeding by the stripping of a proton from the incident ^{3}He ion. It is expected that the other reactions will also proceed directly and that the ^{15}N(^{3}He, α)^{14}N reaction will go by neutron pickup, the ^{12}C(^{3}He, p)^{14}N by two-particle stripping, and the ^{16}O(d, α)^{14}N reaction by two-particle pickup.

Much of the usefulness of direct interactions to nuclear spectroscopy lies in the fact that the angular distributions of the emitted particles characterize the orbital angular momentum transferred in the excitation of a particular state. Unfortunately, in the study of unbound states this usefulness is diminished. Q values of the unbound states of ^{14}N are such that the structure of the angular distributions becomes washed out. Unambiguous identification of orbital angular momentum transfer is then no longer possible.

Nevertheless, considerable spectroscopic information can be extracted by comparing the spectra of the different reactions. For example, it is expected that the excitation of single-particle states will be favored in the ^{13}C(^{3}He, d)^{14}N reaction, whereas the ^{12}C(^{3}He, p)^{14}N reaction will favor two-particle states as well. Thus, it is reasonable to infer that states strongly excited by the (^{3}He, p) reaction and not by the (^{3}He, d) reaction correspond to the excitation of two particles out of the ground-state configuration of ^{14}N. In a similar fashion the ^{15}N(^{3}He, α)^{14}N reaction probably will strongly excite hole states.

Furthermore, the two-nucleon transfer reactions are expected to obey certain selection rules which may permit inference of spectroscopic information from the spectra. For example, the ^{16}O(d, α)^{14}N reaction should not be able to excite $T=1$ states of ^{14}N. Thus, the implication is strong that any intense group in the α spectrum from this reaction corresponds to a $T=0$ state. As will be discussed below, the levels which can be excited by the (^{3}He, p) reaction are also restricted by considerations of isotopic spin.

Of course, intercomparison of spectra from different reactions requires great care. In this respect, ^{14}N is especially suitable for such analysis: So much is already known that conclusions and inferences can be cross-checked with other independently obtained results.

II. EXPERIMENTAL TECHNIQUE

The outgoing particles from the four reactions were analyzed with a 65-cm Browne-Buechner broad-range magnetic spectrograph and recorded on nuclear-track plates. All three ^{3}He-induced reactions used a 15-MeV beam of ^{3}He ions from the University of Pennsylvania tandem electrostatic accelerator. The ^{13}C(^{3}He, d)^{14}N experiment has been described in detail elsewhere.[5] The ^{12}C target was a self-supporting foil of natural carbon $\sim$70 μg/cm^2 thick. The ^{15}N(^{3}He, α)^{14}N and ^{16}O(d, α)^{14}N reactions were studied using gas targets. In the first case the target consisted of nitrogen gas enriched to 99.1% in ^{15}N and contained at a pressure of 20 Torr in a thin-window rotating gas cell of the Hoogenboom type.[6,7] In the second case the target was oxygen gas also at 20 Torr in the same type of gas cell. This target was bombarded with 11-MeV deuterons from the University of Pennsylvania accelerator.

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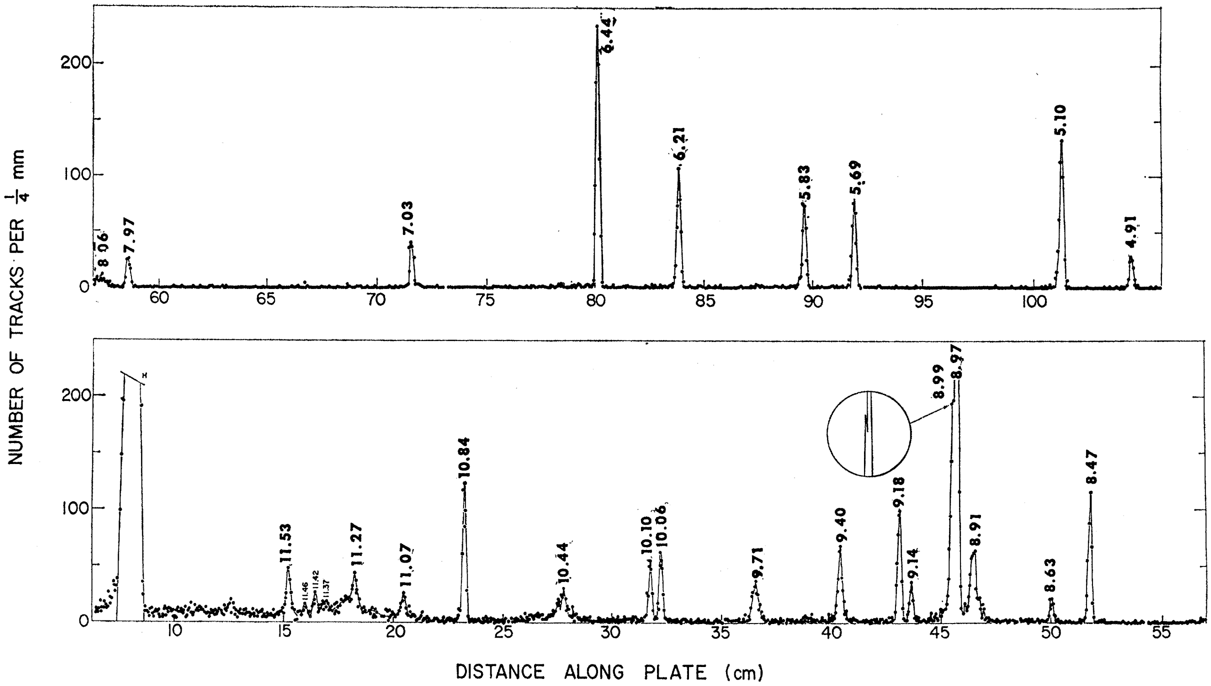

FIG. 1. High-resolution proton spectrum from $^{12}C(^{3}He, p)^{14}N$ reaction at a laboratory angle of 45°. The enlargement of the doublet 8.97–8.99 MeV represents a factor of 2 better resolution and clearly shows there are two peaks here. The magnetic field was set so that groups corresponding to the lowest-lying states do not appear in the spectrum. This procedure makes it possible to record groups corresponding to higher excitation energies in ^{14}N than would otherwise be the case. $E_{^3He}=15$ MeV.

III. RESULTS

Representative spectra of protons, deuterons, and α particles from the various reactions are shown in Figs. 1–4. Peaks are labeled with nominal energies based on old values in the literature; more accurate energies are given in Table II. These spectra were measured at the laboratory angles indicated in the figure captions. Angular distributions were measured only for the groups in the deuteron and proton spectra. With only one or two exceptions the angular distributions of the deuteron groups have been discussed in an earlier paper.[5] Figure 5 shows the angular distributions of proton groups corresponding to states in ^{14}N excited in the $^{12}C(^{3}He, p)^{14}N$ reaction with appreciable intensity up to 12.80 MeV. The angular distributions were measured out to ~60° and exhibit the forward peaking characteristic of direct interactions.

TABLE I. Reactions studied and their Q values.

Reaction	Q value (MeV)
$^{12}C(^{3}He, p)^{14}N$	4.779
$^{13}C(^{3}He, d)^{14}N$	2.056
$^{15}N(^{3}He, \alpha)^{14}N$	9.743
$^{16}O(d, \alpha)^{14}N$	3.111

IV. DISCUSSION

A. Energy Levels

Excitation energies for the levels of ^{14}N were obtained from the spectra of the different reactions. The results are satisfactorily consistent among themselves and there is also good agreement with earlier measurements.[8,9]

The most reliable values are those obtained from the $^{12}C(^{3}He, p)^{14}N$ reaction. These excitation energies, given in Table II, represent averages over several different angles in such a way as to minimize any residual effects of differential hysteresis in the spectrograph magnet. Furthermore, an extremely high resolution measurement of the proton spectrum made at 45° gives results agreeing within a few keV with the averages. In addition, exposures with different spectrograph magnetic fields but otherwise under the same conditions give consistent results.

B. Single-Particle States

Figure 6 shows a comparison of the angular distribution of deuterons from the $^{13}C(^{3}He, d)^{14}N$ reaction leading to the 7.03- and 7.97-MeV states of ^{14}N. Their similarity suggests that these states have the same

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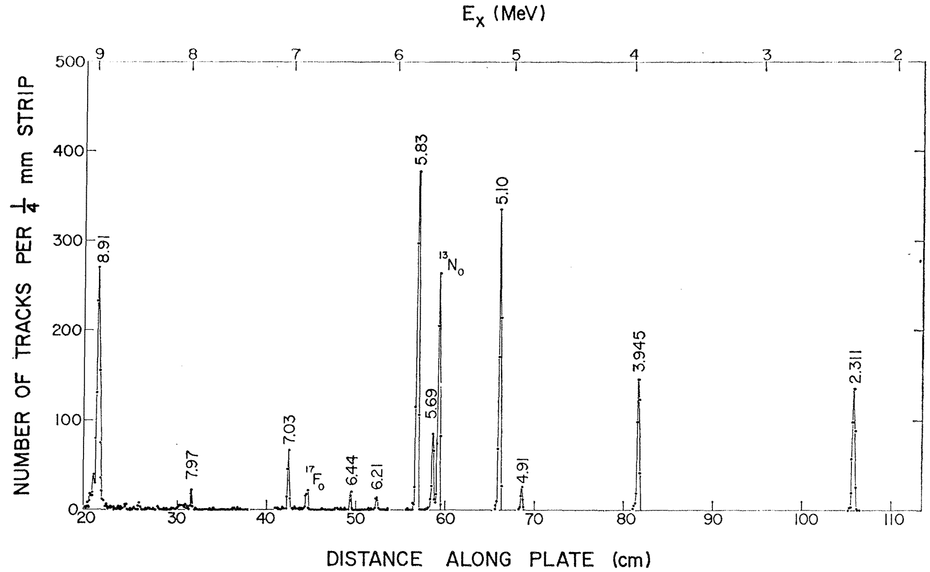

FIG. 2. Deuterons from $^{13}C(^3He, d)^{14}N$ emitted at a lab angle of 15°. The ground-state group was omitted purposely to record the 8.93-MeV state. $E_{^3He}$ = 15 MeV.

parity. Since the 7.03-MeV state is known to be 2^+ and can be excited only by $l=1$ (see Ref. 5), the implication is that the 7.97-MeV state is of even parity and is excited by an $l=1$ transition. This possibility is further supported by the intensity with which this state is excited in the $^{15}N(^3He, \alpha)^{14}N$ reaction. Figure 7 presents four schematic spectra from the four reactions. The relative intensity with which the 7.97-MeV

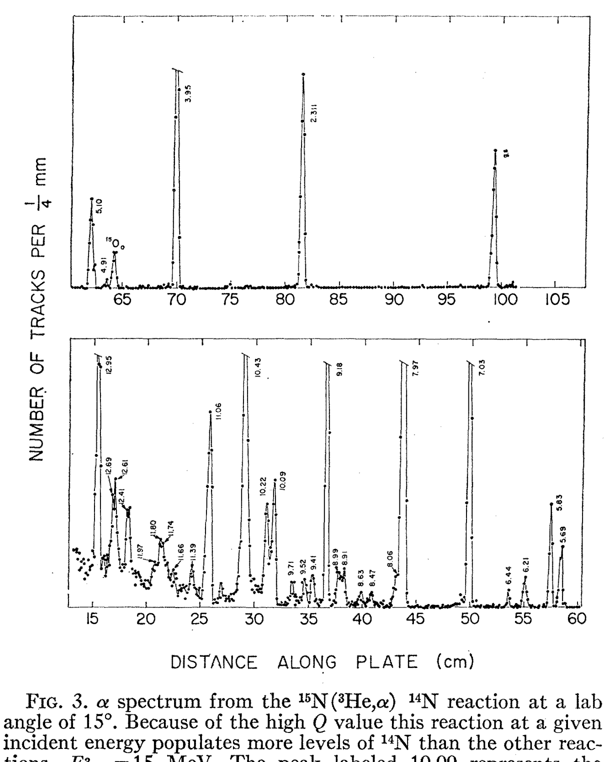

FIG. 3. α spectrum from the $^{15}N(^3He,\alpha)$ ^{14}N reaction at a lab angle of 15°. Because of the high Q value this reaction at a given incident energy populates more levels of ^{14}N than the other reactions. $E_{^3He}$ = 15 MeV. The peak labeled 10.09 represents the unresolved 10.06–10.10-MeV doublet.

state is excited in the $(^3He, \alpha)$ reaction suggests very strongly that it is a hole state excited by picking up a particle from the p shell. This result contradicts the 2^- assignment of Hebbard and Vogl,[10] but it is worth noting that their data rigorously rule out $J=0$ or 3, leaving $J=1$, 2.

^{14}N has four well-known $T=0$ levels at 4.91, 5.10, 5.69, and 5.83 MeV believed to arise from the configurations $p_{1/2}s_{1/2}$ and $p_{1/2}d_{5/2}$. The respective spin and parity assignments of these states are 0^-, 2^-, 1^-, and 3^-. It is of interest to find the corresponding $T=1$ states, and there are four likely candidates.

On the basis of a comparison of calculated transition strengths with experimentally measured ones Warburton, Rose, and Hatch[11] assigned $T=1$ to the levels at 8.06, 8.71, 8.91, and 9.50 MeV. The strength of the 8.91–6.44-MeV γ transition suggests $J=3$ for the 8.91-MeV state, while the strength of the 9.5–5.10-MeV γ transition suggests $J=2$ for the 9.5-MeV state. These suggestions are strongly confirmed by $^{13}C(p, p)$ elastic scattering data[1–3] on the basis of which the levels at 8.06, 8.71, 8.91, and 9.50 MeV have been assigned 1^-, 0^-, 3^-, and 2^-, respectively.

If these are the single-particle states they are thought to be, then they should be excited in the $^{13}C(^3He, d)^{14}N$ reaction. Furthermore, the relative intensities of the members of each configuration should have roughly the ratio of the corresponding statistical factors: 3.0 for the 0^- and 1^- states and 1.4 for the 2^- and 3^- states.

It is certainly clear from Figs. 2 and 7 that the 8.91-MeV state is strongly excited in the $(^3He, d)$ reaction. Furthermore, a comparison of the angular distributions of the deuterons leading to the 8.91- and 5.83-

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TABLE II. Cross sections for excitation of states in ^{14}N by the ^{12}C(^{3}He, p)^{14}N, ^{13}C(^{3}He, d)^{14}N, ^{15}N(^{3}He, α)^{14}N, and ^{16}O(d, α)^{14}N reactions, excitation energies derived from the (^{3}He, p) reaction, and a summary of previous energy, spin, parity, isospin, and configuration assignments.

E_{ex} (MeV)				σ (θ=15°) (mb/sr)[a]			
Present[b] (^{3}He, p)	Previous[c]	J, T	Shell-model configuration	(^{3}He, p) (absolute)	(^{3}He, d) (absolute)	(^{3}He, α) (relative)	(d, α) (relative)
0	0	1^+, 0	$p_{1/2}^2$	1.4	15.0	2.0	>5.0
2.319	2.311	0^+, 1	$p_{1/2}^2$	1.2	10.0	2.5	0.0
3.952	3.947	1^+, 0	$p_{3/2}^{-1}p_{1/2}^{-1}$	2.2	8.3	3.8	2.3
4.927	4.91	0^-, 0	$p_{1/2}s_{1/2}$	0.88	1.0	0.64	1.4
5.117	5.10	2^-, 0	$p_{1/2}d_{5/2}$	3.7	14.0	0.95	3.1
5.713	5.69	1^-, 0	$p_{1/2}s_{1/2}$	1.1	3.2	0.66	0.6
5.885	5.83	3^-, 0	$p_{1/2}d_{5/2}$	0.77	15.0	1.1	1.9
6.224	6.21	1^+, 0	(s, d)	3.3	0.3	0.3	2.0
6.468	6.44	3^+, 0	(s, d)	10.0	0.6	0.1	1.0
7.036	7.03	2^+, 0	$p_{3/2}^{-1}p_{1/2}^{-1}$	0.60	2.0	5.6	3.0
7.974	7.97	0		0.8	0.6	8.7	3.7
8.072	8.06	1^-, 1	$p_{1/2}s_{1/2}$	1.2	0.5	0.3	...
8.493	8.489[d]	4^-, 0		1.8	0.4	0.2	0.9
8.625	8.617[e]	0^+, 1	(s, d)	1.5	0.2	0.2	...
8.912	8.906[e]	3^-, 1	$p_{1/2}d_{5/2}$	6.3	13.3	0.3	0.2
8.97	8.963[d]	5^+		~10 } 13	0.5	} 0.5	} 3.0
8.99	8.979[e]	2^+		~3 }	1.9		
9.126	9.129[d]	2^-, 0		1.2	1.4	...	...
9.176	9.16	2^+, 1	(s, d)+$p_{3/2}^{-1}p_{1/2}^{-1}$	4.2	4.7	3.7	1.2
9.389	9.388[e]	3^-, 2^-		2.8	...	0.4	1.6
...	9.508[e]	2^-, 1	$p_{1/2}d_{5/2}$	0	...	0.3	0.9
9.703	9.702[e]	1^+		1.3	...	0.3	...
10.063	...	0		1.3	...	...	...
10.101	10.092[f]	$1^+(2^+)$		0.80	...	...	1.7
10.441	10.428[f]	2^+, 1	$p_{3/2}^{-1}p_{1/2}^{-1}$+(s, d)	5.4			
10.812	...			3.0			
11.053	11.05[f]	1^+		1.1			
11.249	11.240[f]	3^-		1.2			
11.357	11.30[f]	2^-		2.5			
11.517	11.504[f]			1.8			
12.29				8.0			
12.425				2.9			
12.506				1.4			
12.608				3.5			
12.69				1.7			
12.80				4.4			

[a] Cross sections for the ^{12}C(^{3}He, p)^{14}N and ^{13}C(^{3}He, d)^{14}N reactions are in absolute units ±25%. Cross sections for the ^{15}N(^{3}He, α)^{14}N and ^{16}O(d, α)^{14}N reactions are each in relative units; there is no relation between the relative units for one spectrum and the relative units for the other.

[b] Present results are from the ^{12}C(^{3}He, p)^{14}N data only. Only those states seen in the reactions studied are included in this Table.

[c] As previously summarized or referred to in Ref. 4.

[d] Reference 2.

[e] Reference 3.

[f] Reference 1.

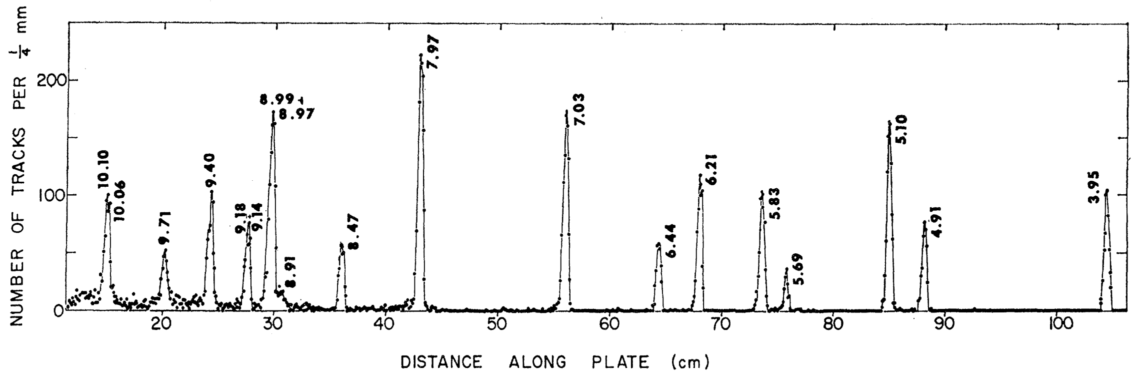

FIG. 4. α spectrum from the $^{16}O(d, \alpha)^{14}N$ reaction at 15° in the lab system. The energy of the incident deuterons was 11 MeV.

MeV states (Fig. 8) indicates they are quite similar. The implication is strong that both states are excited by transitions of the same l value which, according to Holbrow *et al.*,[5] is $l=2$ for the 5.83-MeV state. This result confirms the expected similarity of the configurations and spins of the two states.

The fact that the 8.06-MeV state has appreciable width is consistent with $J^\pi=1^-$ and a configuration of $p_{1/2}s_{1/2}$. (Unfortunately contamination by impurity groups prevents reliable measurement of this width.) The 8.06-MeV state is unbound to proton emission. Although decay would be retarded by the Coulomb barrier, which is $\sim$3 MeV, it would be unimpeded by any centrifugal barrier. Thus, s-wave decay from a $p_{1/2}s_{1/2}$ state to the $\frac{1}{2}^-$ ground state of ^{13}C, which is predominantly $p_{1/2}$, is more favored than any other particle decay.

An interesting check on these assignments is provided by the (^3He, p) reaction. In this case the $p_{1/2}s_{1/2}$ or $p_{1/2}d_{5/2}$ states are excited by the transfer of two nucleons, one into the $p_{1/2}$ orbital and the other into the $s_{1/2}$ or $d_{5/2}$. Conservation of isotopic spin prohibits the

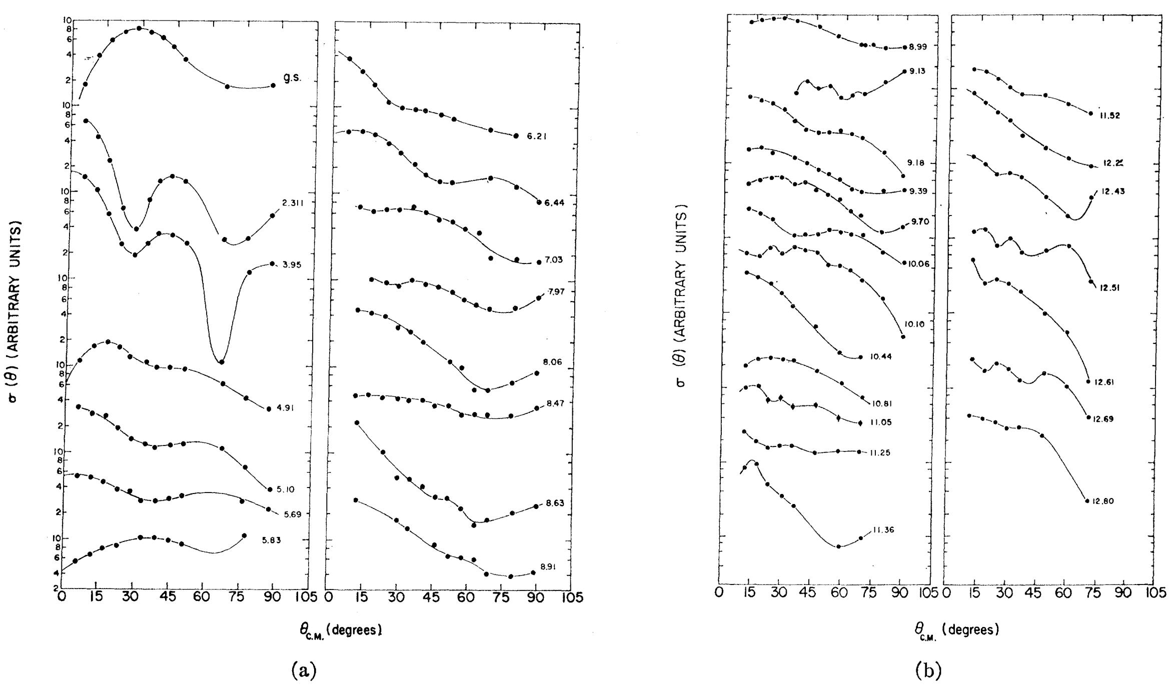

FIG. 5. Angular distributions of protons exciting levels of ^{14}N by the $^{12}C(^3He, p)^{14}N$ reaction. To facilitate illustration they are plotted semilogarithmically. The units of the ordinate axis are arbitrarily chosen. Table II gives the values of the absolute cross sections (±25%) at 15° in c.m. The abscissa is the angle of emission in the c.m. system.

excitation of the 0^- and 2^- states with $T=1$ in this reaction.[12] As expected, neither the 8.71- nor the 9.51-MeV state is appreciably excited. Of course, the small strength of the 8.71 level may be attributable to its spin of 0. Such a contention is supported by the weakness with which this state is excited in the other reactions.

Because these states are presumably single-particle excitations, they are not expected to be seen in the (^{3}He, α) reaction, which will favor hole states. Furthermore, since they are $T=1$ states, they are expected to be completely absent from the ^{16}O(d, α)^{14}N spectrum. All of these expectations are satisfied, as can be seen from Fig. 7.

The 7.03-MeV state discussed above has a well-established configuration of $p_{1/2}^{-1}p_{3/2}^{-1}$ coupled to $J^\pi=2^+$. This is the $T=0$ coupling and this configuration should give rise to a $T=1$, $J^\pi=2^+$ state at higher excitation. Warburton and Pinkston[4] have calculated M1 strengths for transitions of states with $J=2$, $T=1$ to $J=2$, $T=0$ states and have predicted they will be very strong. Experimentally, very strong transitions from 9.16 to 7.03 and from 10.43 to 7.03 MeV have been observed. The sum of the transition strengths is rather close to the calculated value and these authors suggest that both the 9.16- and 10.43-MeV states are 2^+ with a strength being divided between them because of mixing of the $p_{3/2}^{-1}p_{1/2}^{-1} \mid 2^+$ and $d_{5/2}^2 \mid 2^+$ $T=1$ configurations.

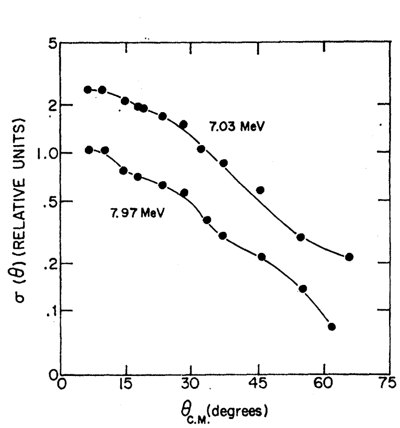

FIG. 6. Angular distributions of deuterons leading to excitation of the 7.03- and 7.97-MeV states of ^{14}N by the ^{13}C(^{3}He, d)^{14}N reaction. The relative differential cross section (±25%) is plotted logarithmically against the c.m. emission angle.

If this suggestion is correct, these two levels would be strongly excited in the (^{3}He, α) reaction, which would reach them through the $p_{3/2}^{-1}p_{1/2}^{-1}$ component, and in the (^{3}He, p) reaction, which would reach them through the $d_{5/2}^2$ component. Examination of the pertinent spectra shows that these two expectations are completely confirmed. On the other hand, the (d, α) reaction should not excite these levels at all, since they are presumed to be $T=1$. Here the evidence is ambiguous because in the (d, α) spectrum used to construct Fig. 7 some evidence for a state at 10.43 MeV was found at the extreme end of the spectrum but part of the group could not be recorded because it was off the plates. This partial group is not shown.

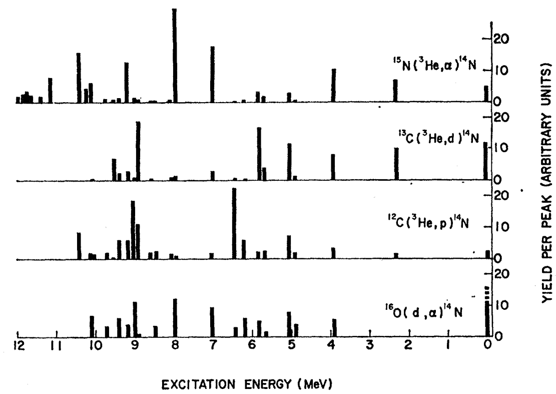

FIG. 7. Schematic representation of spectra from the four reactions. Each spectrum is taken at 15° with respect to the beam in the laboratory system and is normalized to contain a total of 1000 counts. There is no correction for solid angle, which varies by ~2× over the range of the spectrum, being largest at high excitation energies.

C. Angular Distributions

Angular distributions of protons from the ^{12}C(^{3}He, p)^{14}N reaction leading to the low-lying states of ^{14}N show considerable structure. Comparisons among these data are interesting for the low-lying states.

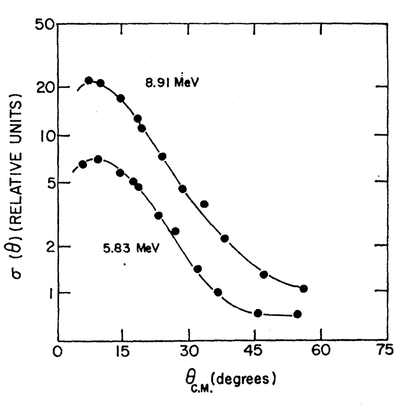

FIG. 8. Angular distributions of deuterons feeding the 5.83- and 8.91-MeV states of ^{14}N by the ^{13}C(^{3}He, d)^{14}N reaction. The relative cross section (±25%) is plotted logarithmically against the angle of emission in the c.m. system. However, to facilitate display the angular distribution corresponding to the 5.83-MeV level has been displaced downward by a factor of 3. The two angular distributions are almost identical in magnitude.

[12] N. K. Glendenning, Phys. Rev. **137**, B102 (1965).

The ground state is known to have $J^\pi=1^+$. The positive parity implies the L value of the angular momentum transferred in this reaction must be even. Consequently the possible L values are limited to 0 and 2. The 2.311-MeV state is $J^\pi=0^+$, $T=1$ and can only be reached by $L=0$ transfer of a $T=1$, two-nucleon cluster. The pronounced forward peaking of the angular distribution leading to the 2.311-MeV state strongly suggests an $L=0$ transfer. However, in a comparison of this angular distribution with the ground state the absence of forward peaking in the ground-state distribution is striking. Apparently the principal contribution to this angular distribution is $L=2$.

The second excited state at 3.95 MeV has $J^\pi=1^+$ and therefore can be excited only by $L=0$ and 2. Its angular distribution is markedly similar to that of the 2.311-MeV state. Apparently there is very little excitation of the 3.95-MeV state by $L=2$ transfer.

Excitation of the 0^-, 4.92-MeV state can proceed only by $L=1$ transfer. The angular distribution is consistent with this restriction, exhibiting a forward minimum and peaking at about 17°. The fact that the presumed $L=2$ angular distribution leading to the 3.95-MeV state peaks at 25° is consistent with the L values assigned to these angular distributions.

In general, the angular distributions of particles emitted in a two-nucleon transfer reaction will not be simply related to the transferred angular momentum.[12] Interference effects are well known both in theory and experiment. Thus it is not surprising that the angular distribution leading to the 2^-, 5.10-MeV state peaks at 0°, even though it can only proceed by $L=1$ and 3 transfer. Interference between the wave-function amplitudes corresponding to the different orbital angular momentum L values can account for the observed shape.

Interference effects will become more important as the configurations become more complicated, as tends to be the case at higher excitation energies. Also, characteristically, structure in angular distributions washes out as excitation energy increases. Therefore, angular distributions to levels in ^{14}N above 6 or 7 MeV in excitation are uninformative without detailed distorted-wave analysis.

Mangelson and Harvey[13] have made such analyses of their $^{12}C(^3He, p)^{14}N$ data taken at $E_{^3He}=20.8$ MeV with ~80-keV resolution. Their angular distributions are very similar to ours. Our own preliminary distorted-wave Born-approximation (DWBA) calculations agree closely with theirs, but in view of the attendant difficulties and uncertainties of interpretation it does not seem useful to do more than publish our experimental distributions. They are presented in Fig. 5, with the cross sections given in arbitrary units. The pictured data may be converted to absolute cross sections in mb/sr by using the absolute cross sections at 15° c.m. tabulated in Table II. They are estimated as accurate to ±25%.

D. Two-Particle States

The 6.21- and 6.44-MeV states have $J^\pi=1^+$ and 3^+ and are thought to arise from the $s^4p^8(sd)^2$ configuration. They correspond to the 1^+ ground state and 3^+ level at 0.94 MeV in ^{18}F. The 9.16- and 10.43-MeV levels of ^{14}N share the configuration corresponding to the 2^+, 3.06-MeV state of ^{18}F. Because ^{18}F has a 5^+ and a 0^+ state at 1.13 and 1.04 MeV, respectively, it is reasonable to look for similar states in ^{14}N between 6.44 and 9.16 MeV.

The 0^+ $T=1$ level will exhibit a strong $M1$ $\Delta T=1$ γ transition to the 6.21-MeV state. (Warburton and Pinkston[4] estimate $M^2=10$ Weisskopf units relatively independent of wave function.) Such a transition has been observed from the 8.62-MeV level of ^{14}N. Results from studies of the $^{13}C(p, p)$ elastic scattering determine 0^+ for this level,[1,3] so that it is likely to be the state sought. As a $T=1$ state it should not appear in the (d, α) spectrum, and as a 0^+ arising from $s_{1/2}{}^2+d_{5/2}{}^2$ it should be excited strongly only by two-nucleon transfer as in the $(^3He, p)$ reaction and not by $(^3He, d)$ or $(^3He, \alpha)$. Figure 7 shows this to be the case, thereby tending to support the earlier work.

The search for the 5^+ level of the (sd) configuration is much simplified because its excitation is kinematically favored in two-nucleon transfer reactions. Such a state will correspond to the insertion of a deuteron in the $(^3He, p)$ or (α, d) reactions and the withdrawal of one in the (d, α) reaction. Cerny, Harvey, and Pehl[14] have studied the systematics of the excitation of 5^+ states in various nuclei using 30–40-MeV ^3He and α particles to induce the $(^3He, d)$ and (α, d) reactions. The 5^+ states of the $d_{5/2}{}^2$ configuration stand out very strongly in their spectra compared to other states. They observed[15] such a state, which they assigned to 8.99 MeV in ^{14}N, where a state had previously been identified as 2^+. However, in the spectrum in Fig. 1 there is quite clearly a doublet at 8.97 and 8.99 MeV. The stronger of the two is the 8.97-MeV state, and we identify this as the 5^+. This result is in agreement with Detenbeck *et al.*,[2] who identified a midget resonance in the $^{13}C(p, p)$ excitation curve as corresponding to a 5^+ state in ^{14}N at 8.963 MeV, and is not inconsistent with the relatively low-resolution results of Harvey *et al.* Since this 5^+ state is a $T=0$ two-particle state, it should also appear strongly in the (d, α) spectrum; the appearance of a strong state in this region supports the assignment.

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V. CONCLUSIONS

The nature of 7.97-MeV state must be looked into more carefully. It seems clear that it is a positive-parity hole state, but its configuration remains to be determined.

Comparison of spectra from the ^{13}C(^{3}He, d)^{14}N, ^{12}C(^{3}He, p)^{14}N, ^{15}N(^{3}He, α)^{14}N, and ^{16}O(d, α)^{14}N reactions lends strong support to previous spin, isospin, parity, and configurational assignments of the 8.06-, 8.70-, 8.91-, 8.96-, 9.18-, 9.51-, and 10.43-MeV states.

Excitation energies were measured from ± 15 keV up to 12.8 MeV, and the doublet at 9.13 and 9.18 MeV was observed, as was the doublet at 8.963 and 8.979 MeV [previously seen only in ^{13}C(p, p)]. A doublet was also observed at 10.06 and 10.10 MeV.

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Hartree-Fock-Bogoliubov Calculations in the 2s, 1d Shell

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Ground-state properties have been studied for $N=Z$, $N=Z+2$, and $N=Z+4$ even-even nuclei for which both neutrons and protons fill the 2s, 1d major shell, using the Hartree-Fock-Bogoliubov theory. The mass quadrupole moments and moments of inertia relative to the intrinsic reference frame are calculated, and qualitative features of the intrinsic deformations are discussed. Comparison is made to the results obtained when pairing correlations are absent, i.e., the Hartree-Fock predictions. The Hartree-Fock-Bogoliubov calculation yields the Hartree-Fock results for $N=Z$ even-even nuclei.

I. INTRODUCTION

SEVERAL treatments of the Hartree-Fock-Bogoliubov (HFB) theory have appeared in the literature,[1–4] but explicit numerical calculations with this method that use anything but schematic forces (e.g., the pairing plus quadrupole model) have been rather scanty to date, because of the complexity of the formalism and the formidable amount of numerical manipulation involved. The HFB theory, also known as the generalized Hartree-Fock (HF) method, treats both field-producing effects and pairing effects due to nuclear interactions in a self-consistent fashion. It is, therefore, expected to be better than either HF or the conventional BCS theory.

The present study deals with even-even nuclei in the region from ^{16}O to ^{40}Ca; we include only contributions from 2s, 1d shell configurations. Section II outlines the main features of the HFB theory; most of these results are not original. Section III deals with the relation of HFB to the BCS and HF methods sometimes used to describe deformed intrinsic states, and Sec. IV contains the results of the numerical calculation.

II. HFB THEORY

The unique feature of this formalism is the generalized Bogoliubov transformation, which relates single-particle creation and annihilation operators in a shell model (j, m) basis to quasiparticle creation and annihilation operators which are convenient for the description of pairing phenomena, by a general linear canonical transformation. We partition the $2M$ basis states that span a major shell into a particular set of M states and their M time-reversed states. (For the 2s, 1d shell,

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