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SPECTROSCOPY OF ^{14}N BY USE OF THE ^{12}C(^{3}He,p)^{14}N REACTION[†]

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Abstract

Spectra and angular distributions were obtained for the reaction ^{12}C(^{3}He,p)^{14}N at E(^{3}He) = 20.1 MeV from θ_{lab} = 8° to 170°. Distorted-wave calculations were compared to experimental angular distributions and relative total cross sections. Agreement was found when a spin-independent interaction potential was used. Nuclear wave functions used in the calculations are discussed.

Spectorscopic and configuration assignments were made or confirmed on the basis of excitation energy, angular distribution, comparison of (α,d) and (^{3}He,p) results, relative total cross sections, and comparison of experimental results with distored wave Born approximation calculations. A spin and parity assignment of 2^- and a tentative assignment of 4^+ were made for the 9.388 and 10.85 MeV, T = 0 levels repsectively. Suggested configurations were made for the 8.979, 10.213 and 10.85 MeV levels.

[†] Work performed under the auspices of the U. S. Atomic Energy Commission.

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E

NUCLEAR REACTIONS $^{12}C(^3He,p)$,E = 20.1 MeV; measured $\sigma(E_p,\theta)$.
^{14}N deduced J,π,ℓ. Natural target.

1. Introduction

Two-nucleon transfer reactions have been shown to be useful for the study of nuclear spectroscopy and particularly well suited for testing theoretical nuclear wave function1). The proposed mechanisms and some applications of this class of reactions have recently been examined in detail2-4). These studies all indicate that the proposed dynamics of the reactions are reasonably well accounted for by present distorted wave (DW) theories1,5), but point up a need for additional study of some of the assumptions made.

This study was undertaken to further test the usefulness of two-nucleon transfer theory in the region of light nuclei-- specifically the reaction $^{12}C(^{3}He,p)^{14}N$ at $E(^{3}He) = 20.1$ MeV. It was further hoped that an examination of data from this reaction, which populates both $T = 1$ and $T = 0$ states1), together with a comparison of data from the $^{12}C(\alpha,d)^{14}N$ reaction6,7), which populates only $T = 0$ states, would yield spectroscopic information about ^{14}N. Nuclear wave functions for the ^{12}C ground state and for ^{14}N ground and excited states were to be tested by a comparison of calculated relative differential and total cross sections to corresponding experimental values. The $^{12}C(^{3}He,p)^{14}N$ reaction has also been studied by other workers and their work will be discussed in sect. 4.

2. Experimental Method and Results

A ^{3}He beam from the Berkeley 88-inch variable-energy cyclotron was used with experimental equipment described earlier8). A Goulding-Landis particle identification system9) was used to determine particle energy and type. Energy pulses were analyzed and stored in a Nuclear Data ND-160 analyzer.

An evaporated self-supporting ^{12}C foil of 280 ± 25 μg/cm^2 thickness was used in the study. On the basis of protons observed from the reaction $^{16}O(^3He,p)^{18}F$, oxygen impurity was estimated to be 1-2% and impurity peaks seen in elastic ^3He scattering on a similar ^{12}C target suggested less than 2% impurities from elements other than oxygen and hydrogen.

A proton energy spectrum taken at $\theta_{lab} = 30.4°$ is shown in fig. 1. The full-width at half maximum (FWHM) of a spectrum peak for a "sharp" level appeared to vary with proton energy (i.e. with analyzer channel number). The FWHM ranged from about 80 keV at channel number 300 to ≈ 150 keV at channel number 600. This may have been due to the slower rise time of the energy pulse as protons penetrated deeper into the E detector.

Background counts were arbitrarily subtracted from each spectrum as follows. No subtration was made below an excitation of approximately 8 MeV. By inspection a line was drawn from zero counts at 8 MeV with a slope increasing in counts with excitation energy. The line was drawn below the valleys of the spectrum. A second line was similarly drawn with a sharper rise vs. excitation energy and intersecting the first at about 10.5 MeV. All counts below these two lines were subtracted as background.

The assignments of excitation energies to levels of ^{14}N observed in this experiments were based on 1) known excitation energies for the lowest few levels of ^{14}N and 2) a proton peak corresponding to the $^1H(^3He,p)^3He$ reaction (see fig. 1). Because of this latter impurity peak, confidence was placed in the energy assignments of levels in the region of 12-MeV excitation energy. Observed excitation energies are listed in table 1. Angular distributions$^{10,11)}$ for a number of levels are shown in figs. 4-8. Errors on the experimental points represent statistical error only.

Total cross sections calculated between 10° and 70° center of mass are listed in table 1. The following estimated errors affect the relative cross section: statistical error 5-10%, background subtraction 1-10% (for the states above 9 MeV) -- errors for the strong states are the low limits. In addition to these errors the following would affect the absolute cross section: beam integration 3%, dead time and other electronic errors 2%, uncertainty in target thickness 10%. From these estimates relative total cross sections should agree within 5% - 15% depending on the strength of the state. The absolute cross sections are expected to vary from 15% - 20% for levels below 9 MeV and, due to errors in background subtraction, from 20% - 30% for high excited levels.

3. Spectroscopy by Examination of Data and Comparison to Other Work

Table 1 contains a listing of all the known levels of 14) below an excitation energy of 13.2 MeV and a few additional levels above this energy which are applicable to the two-nucleon transfer reaction under discussion. The energies listed in column one and the spin, parity and isospin assignments are those in the compilation of Ajzenberg-Selove and Lauritsen12) or are taken from the references listed. The third column contains the experimentally determined excitation energies and errors obtained in this work.

The fourth column contains the integrated cross sections between 10° and 70° center of mass from the present experiment. These limits were chosen to give a constant range of intergration for all levels and in addition, this is the region of best agreement between the experimental and theoretical angular distributions. The dominant configurations of the energy levels are given in cases were they have been assigned with the mixing coefficients taken from the calculations of True13) and Cohen and Kurath14).

Selection rules for (^{3}He,p) reactions have been discussed by Glendenning$^{1)}$. For this reaction on a target of spin zero, the spin J_2 and isospin T_2 of the final state are just equal to the transferred quantities J and T. For final states of isospin one, the intrinsic spin S transferred must be zero; and, therefore, the final state spin J_2 equals L, the transferred angular momentum. Inasmuch as the parity of the final state is odd or even as L is odd or even, T = 1 states of unnatural parity are forbidden in the reaction. Note that the 8.71 and 9.508 MeV levels are unnatural-parity states of T = 1 and are, therefore, not allowed. Neither of these levels is observed above the tail of the neighbor level peak.

For final states of isospin zero the intrinsic spin transfer is one. In this case

$$J_2 + 1 \geq L \geq |J_2 - 1|$$

and L must be odd or even as the parity of the final state is odd or even. All T = 0 natural-parity states are, therefore, restricted to a single value of L transferred as in the case of T = 1 states; however, for T = 0 unnatural-parity states, two values of L are allowed by the selection rules. The proper mixing of the two allowed L values in a transition can be a sensitive measure of the correctness of a theoretical calculation as will be seen in sect. 5.

By the selection rules, as just discussed, transitions to a number of levels in ^{14}N via the ^{12}C(^{3}He,p)^{14}N reaction are restricted to a single L value. These restricted transitions can be used to identify the angular distribution shape peculiar to a given L transfer. Figures 4 to 6 contain angular distributions for transitions proceeding entirely or predominatnly via L = 0, 1 and 2 respectively. Figure 7 contains L = 3 and 4 angular distributions.

The 8.489 MeV level has been assigned J = 4^- by Detenbeck et al.[31]) who suggest a $(p3/2)^{-1}(p1/2)^2(d5/2)$ configuration for this state. The observation[6,7]) of this level in the reaction $^{12}C(\alpha,d)^{14}N$ confirms the T = 0 assignment. By spin selection rules both L = 3 and 5 transitions are allowed for this state. The above proposed configuration would, however, restrict the L to a value of 3 only. As can be seen in fig. 7, this transition does proceed by an L = 3 transition which confirms the negative-parity assignment and is consistent with the suggested configuration.

All of the known energy levels of ^{14}N below 8.7 MeV excitation energy were resolved in the present work. Three levels near 9 MeV were, however, not resolved. The level of lowest energy in this group is known 3^-, T = 1 level. The next level is the giant level seen by Harvey et al.[34]) in the $^{12}C(\alpha,d)^{14}N$ reaction, and assigned by them to be $J^\pi = 5^+$. Detenbeck et al.[31]) have also measured the excitation energy of this level and confirmed the 5^+ assignment.

The third level of the group has been studied by Latorre and Armstrong[28]). They have assigned a spin and parity of 2^+ and a configuration of (2s,1d) to this level. In the calculations by True[13]) for levels of ^{14}N a 2^+ T = 0 state of (2s,1d) configuration is predicted at an excitation energy of 8.8 MeV. This level was associated with the known level of ^{14}N at 10.09 MeV. Kashy et al.[38]) have shown a preference for a 1^+ assignment for the 10.09 MeV level although the 2^+ value could not be eliminated as a possibility. On the basis of these data, the 2^+ T = 0 level predicted by True[13]) to be at 8.8 MeV is assigned to the known 2^+ T = 0 level of ^{14}N at 8.979 MeV.

The 9.388 MeV level has also been studied by Latorre and Armstrong[28]) and they restrict the spin and parity assignment of this level to 2^- or 3^-. By the spin and parity selection rules only an L = 3 transition is possible for a 3^- spin and parity assignment. Both L = 1 and 3 are allowed for a 2^-

assignment. A comparison of the angular distribution of this level with other $L = 1$ transitions (fig. 5) indicates that the transition to the 9.388 MeV level of ^{14}N is predominantly $L = 1$ which restricts the spin and parity of this level to a value of 2^-.

Rose et al.[24]) have shown the 10.213 MeV level to be of spin and parity 1^+ and, further, that the level is most likely $T = 0$. This level was not observed by Pehl et al.[7]) and Zafiratos et al.[6]) in the $^{12}C(\alpha,d)^{14}N$ reaction. As indicated in table 1, this level was not observed in the $(^3He,p)$ reaction. (In fig. 1 the position of this level is indicated and a small peak is apparent at this excitation energy; however, this is the only spectrum, among all those taken, which has a peak at this excitation energy.) A 1^+ $T = 0$ level predicted by True[13]) at a calculated energy of 9.3 MeV was associated by him with the 9.702 MeV 1^+ $T = 0$ level of ^{14}N which level was observed in the (α,d) and $(^3He,p)$ reactions. As is noted in sect. 5, True's 1^+ $T = 0$ level is not expected to be observed and for this reason the predicted level is tentatively reassigned to the 10.213 MeV level of ^{14}N which, as mentioned above, was not observed.

The 10.85 MeV level of ^{14}N is strongly excited in the $^{12}C(\alpha,d)^{14}N$ reaction[6,7]). This suggests that the level has a high spin and $T = 0$. The angular distribution of protons from the $^{12}C(^3He,p)^{14}N$ reaction exciting this level, as shown in fig. 7, indicates a transition of $L = 3$ or greater. Calculations by True [13]) indicate that transitions in this region should involve $L = 4$ or less. The spin and parity of this level are then restricted to values of 2^-, $3^{\pm}$, $4^{\pm}$, 5^+. The strong population of this level suggest that it has a simple, two-particle configuration. All of the energy levels of ^{14}N predicted by True[13]) below an excitation energy of 10 MeV have been uniquely associated with known levels of ^{14}N. It is therefore reasonable to attempt to associate a level predicted by True with this ^{14}N level. By the spin and parity restrictions discussed above, only two predicted levels can be considered: a 3^+ T = 0 at 11.0 MeV and a 4^+ T = 0 at 10.8 MeV. As is noted in sect. 5, a transition to the 3^+ would be very weak while a transition to the 4^+ would be very strong. On this basis the 10.85 MeV level of ^{14}N is tentatively assigned 4^+ T = 0. The configuration predicted by True is indicated in table 1.

A region of levels between 12.4 MeV and 13.2 MeV was strongly populated by the reaction under discussion by the $^{12}C(\alpha,d)^{14}N$ reaction[6,7], and by the reaction $^{12}C(^{11}B,{}^{9}Be,)^{14}N$ reaction carried out by Sachs, Chasman and Bromley[36]. A 4^+ T = 1 state of $(d5/2)^2$ configuration is predicted by True to be at an energy of 12.0 MeV. A comparison between the (α,d) reaction, which could not excite a T = 1 state, and the $(^3He,p)$ reaction, which could excite the T = 1 state, should allow identification of T = 1 levels in this region. Two levels in this region are proposed to be 4^+. One of these may be the T = 1 $(d5/2)^2$ level. As is shown in table 1, five levels can be individually resolved in the data from the $^{12}C(^3He,p)^{14}N$ reaction. A composite peak containing three levels is also observed.

The (α,d) data of Pehl et al.[7] has insufficient energy resolution for comparative purposes, while data of Zafiratoes et al.[6] has better energy resolution and should be useful for comparison. These workers report a very strong peak at an excitation energy of 13.05 MeV. An examination of fig. 1 reveals that an excitation of 13.05 MeV in ^{14}N is in the region of a sharp minimum between the 12.95 and 13.17 MeV levels indicating very little excitation of a level at this excitation energy. It seems quite unreasonable to suppose a level so strongly populated in an (α,d) reaction would not be excited at all in a $(^3He,p)$ reaction. Data from both reactions have been carefully checked[6] in an effort to solve this apparent discrepancy in excitation energy assignments, nevertheless the discrepancy still remains. It is therefore, not possible to assign the 4^+ T = 1 state by a comparison of the results from the two reactions with these data.

Figure 6 contains a group of L = 2 angular distributions. There is a distinct difference between the angular distributions for the ground state and the 7.029 MeV levels in comparison with that for the 6.44 MeV level. The two former levels are of $(p)^{-2}$ configuration while the latter is of an $(s,d)^2$ configuration. These data suggest that angular distributions may be dependent to some degree upon details of nucleon structure and not just to the L-transfer.

4. Discussion of Reaction Mechanism and Stripping Theory

The $^{12}C(^3He,p)^{14}N$ reaction has been studied by several workers. Holbrow et al.$^{18)}$ and Priest et al.$^{40)}$ studied this reaction at a ^{3}He energy of 14 MeV. The latter obtained angular distributions to the ground state and first two excited states of ^{14}N (see fig. 2). Rivet$^{41)}$ obtained angular distributions to the ground state and first two excited states of ^{14}N at a ^{3}He energy of 31 MeV.

Hinds and Middleton$^{42)}$ obtained excitation functions at 10° laboratory for the ground state and six excited states of ^{14}N from the (^{3}He,p) reaction at ^{3}He energies of 5.7 to 10.23 MeV. All excitation functions show strong fluctuations over this energy range. Angular distributions for these levels were taken at several energies. Angular distributions for the ground state of ^{14}N all peak at zero degrees except the angular distribution at E(^{3}He) = 10.14 MeV (see fig. 2). At this energy the angular distribution has a maximum at approximately 30° c.m. and then decreases at smaller angles.

At ^{3}He energies higher than 10 MeV the transition to the ^{14}N ground state continues to show an angular distribution decreasing at zero degrees with a first maximum moving from about 25° c.m. to 15° as the energy is increased from 14 MeV[72]) to 31 MeV[4]). It will be shown in sect. 5 that the transition ^{12}C(^{3}He,p)^{14}N to the ^{14}N ground state, if a direct two-nucleon stripping transition, should proceed predominatnly by an L = 2 transfer. The angular distribution shape just discussed is an L = 2 shape (see fig. 6). The change in the form of the ground state angular distribution in the energy region of 5 to 10 MeV suggests a changing reaction mechanism in this region.

Angular distributions for ^{14}N states at 2.311 MeV and the 3.945 MeV also show a change in character between 5.98 and 10.14 MeV incident ^{3}He energies, although the change is not as pronounced as in the case of the ground-state transition. It is also interesting to note that the envelope of the angular distributions for all energies is nearly flat for angles larger than 60° or 70° center of mass. If this constant cross section at back angles were due entirely to compound-nuclear effects, the cross section envelope might be expected to decrease at higher ^{3}He energies. The fact that this trend is not observed suggests that effects other than compound-nuclear effects also influence the back-angle cross sections.

Fulbright et al.[43]) have measured, simultaneously, excitation functions of the differential cross sections at 10° laboratory for the reactions ^{12}C(^{3}He,p)^{14}N and ^{12}C(^{3}He,n)^{14}O to the ground state of ^{14}O and the ^{14}N analog state at 2.311 MeV excitation energy. ^{3}He energies ranged from 6.5 MeV to 11 MeV. The excitation functions showed a strong energy dependence and neutron and proton angular distributions showed a forward peaking characteristic of direct reactions. Total and differential reaction cross sections for the reaction

$^{12}C(^{3}He,n)^{14}O$ have also been measured by Osgood et al.^{44}) and by Deshpande et al.^{45}) for ^{3}He energies below 11 MeV. These workers also found strong energy dependence in the cross sections for this reaction. These data suggest that $^{12}C(^{3}He$,n or p) reactions proceed in large measure by compound-nucleus mechanism below an energy of at least 12 MeV.

Manley^{19}) has obtained angular distributions for neutrons from the reaction $^{12}C(^{3}He,n)^{14}O$ to the ground state of ^{14}O at ^{3}He energies of 19, 22, and 25 MeV. The differential cross section at 0° and 19 MeV ^{3}He is about 3.4 mb/sr. This value is in good agreement with a value of $2 \times 1.8 = 3.6$ mb/sr obtained by extrapolating to 0° data reported herein for the reaction $^{12}C(^{3}He,p)^{14}N$ to the 2.311 MeV analog state. The factor of 2 is necessary to correct for the different value of b_{ST}^{2} in the two reactions^{1}). Bryant et al.^{46}) have measured the differential cross section at 0° for the (^{3}He,n) reaction on ^{12}C at 25 MeV ^{3}He and obtained a value of 4.3 ± 0.6 mb/sr which is in reasonable agreement with these data and the 31 MeV data of Rivet^{41}).

Manley and Stein^{47}) studied the (^{3}He,n) reaction at 19, 22 and 25 MeV ^{3}He on a number of nuclei from Be to Ag with oxygen included as one of the targets. These data together with data taken by Manley^{19}) on carbon at the same energies were analyzed to determine the proportion of direct mechanism and compound-nuclear mechanism contributing to the reactions at the energies studied. Their work suggests that for the two-nucleon transfer reaction studied the excitation of low-lying states, particularly for small scattering angle, is predominantly by a direct reaction mechanism. It also suggests that back-angle cross sections include contributions from compound-nucleus mechanisms.

In summary the following can be noted. The model used by Manley and Stein^{47}) was very simple and their application of it gave only qualitative information. The excitation functions discussed were taken at energies about one half of that used in the experiment reported herein. Comparison of a few data in the energy region of this experiment suggests a smoothly varying excitation function. From these considerations a quantitative determination of the amount of compound-nuclear contribution to reactions studied cannot be made. It is, however, safe to conclude that compound-nuclear contributions are significant in the differential cross sections at angles greater than about 90° center of mass.

Possible multi-step mechanisms involving inelastic excitations in the entrance and exit channels of direct reactions have been discussed by a number of workers48). Recently, Fleming et al.2) have shown evidence for a possible multiple step excitation in the $^{13}C(p,^{3}He)^{11}C$ reaction. In ^{12}C the B(E2) for the quadrupole transition between the 0^{+} ground state and the 2^{+} 4.43 MeV excited state is 5 - 8 times the single-particle B(E2)49). This strong coupling suggests the possibility of a two-step mechanism in the (^{3}He,p) reaction under consideration. The spectroscopic factors for two-nucleon transfer between the ^{12}C 2^{+} state and states of ^{14}N must, however, be compared to spectroscopic factors for the direct, single-step process before an estimate of the magnitude of multi-step processes can be made.

Following, in general, the work of Glendenning1), a brief outline of the direct reaction, two-nucleon stripping formalism is here shown. Let the reaction be defined by expression (1).

$$\begin{aligned} a + A &\rightarrow b + B \\ b + x &= a \\ A + x &= B \end{aligned} \tag{1}$$

The light particles involved are a and b, the target and product are A and B respectively, and the transferred neutron and proton are represented by x .

When the spin of A is zero, the center-of-mass differential cross section may be represented as follows.

$$\frac{d\sigma}{d\Omega} \propto \frac{k_2}{k_1} (2J_2 + 1) \Sigma_{LSJT} C_{ST}{}^2 \Sigma_M \left| \Sigma_N G_{NLSJT} B^M_{NL} \right|^2 \tag{2}$$

k_1 and k_2 are wave numbers in the entrance and exit channels respectively and J_2 is the total spin of the product B. L,S,J and T are the orbital angular momentum, intrinsic spin, total spin and isospin transferred by x. The center-of-mass motion of x in the final state B is described by NLM where N is the principle quantum and M is the projection of L on the quantization axis.

The factor G_{NLSJT} is the amplitude for the transferred pair to have their motion in the product B described by the center-of-mass state NL and other quantum numbers SJT when their relative motion matches what it was in the light nuclide. B^M_{NL} is the amplitude for transfer of a "particle" x with mass 2 and motion NLM. This factor may be calculated according to usual distorted wave (DW) methods.

$$C^2_{ST} = |\langle T_1 T_{z_1} T\ T_x\ T_2 T_{z_2} \rangle|^2\ b_{ST}{}^2\ D(s)^2 \tag{3}$$

The Clebsch-Gordon coefficient couples the transferred isospin T with that of the target T_1 to give the isospin of the product T_2. The factor b^2_{ST} is the spin-isospin spectroscopic overlap of x and b in the final state with a, their initial state.

In the DW approach usually taken for direct reactions, the interaction responsible for the stripping process is a two-nucleon potential ${}^{T'S'}V$, acting between the scattered proton b and each of nucleons in x. T'S' are the isospin and spin of a pair b plus one of the nucleons of x, which is in contrast to TS which are the isospin and spin of the transferred pair x. Fleming et al.$^{2)}$ and Hardy and Towner$^{3)}$ have shown that if ${}^{T'S'}V$ is spin independent, i.e. if ${}^{13}V \equiv {}^{31}V$ the factor D(s) is equal to unity for both S = 0 or 1; but if, as is to be expected$^{2,3)}$, ${}^{13}V > {}^{31}V$ then D(s) is less than one for both values of S and further

$$D(S = 1) < D(S = 0) \quad .$$

Fleming et al.$^{2)}$ in comparing relative cross sections for the reactions (p,t) and (p,^{3}He) find an improved agreement between theory and experiment when a spin-dependent interaction potential is used, nevertheless agreement is not reached in several cases and they discuss other possible effects which may be simultaneously affecting relative cross sections.

Hardy and Towner$^{3)}$ have calculated the ratio $R(S) = |D(S{=}1)/D(S{=}0)|^2$ for several effective interactions used in nuclear structure calculations and found values of 0.4 to 0.6. These workers further suggested that ${}^{12}C({}^{3}He,p){}^{14}N$ is a reaction which could be used to experimentally test this spin-dependent effect. By selection rules$^{1)}$ transitions to the ^{14}N ground state (g.s.) and 3.945-MeV states may proceed by both S = 1, L = 0 and S = 1, L = 2 while the transition to the 2.311-MeV state is restricted S = 0, L = 0. Hardy and Towner$^{3)}$ 1) assumed an expression like eq. (2) for the cross section of each of these states, 2) neglected the sum on N, 3) supplied values of G_{NLSJT} based on a pure LS state for ^{12}C g.s. and Cohen and Kurath$^{14)}$ calculations for ^{14}N wave functions, 4) used experimental cross sections from the present work, and 5) solved the set of three simultaneous equations to find a value of R(S) = 0.52.

When the calculation of R(S) is made following the method just described but using the Cohen and Kurath[14] ^{12}C g.s. wave function, a value of R(S) = 1.14 is found which indicates this experimental test of the idea is strongly dependent on assumed wave functions. Similar calculations were made for data taken at 10.14[42], 13.9[40], and 31.2 MeV[41] and the results are shown in table 2.

In summary, the spin dependent force is to be expected; however, 1) the failure of this effect alone to explain the observations of Fleming et al.[2] 2) the apparent difference in the magnitude of the effect in this present work when using different ^{12}C wave functions, and 3) the changing R(S) value for various ^3He bombarding energies all indicate that other effects[2] are also important and the strength of the spin-dependent force cannot be accurately determined with these data. It has been found that for the DW calculations discussed below the assumption of a spin-independent force allowed a reasonable fit to the data. Calculations for the $^{16}O(^3He,p)^{18}F$ reaction at 20 MeV[11] and 18 MeV[50] also required a spin-independent force.

5. Distorted-Wave Calculations

A DW calculation for the reaction $^{12}C(t,p)^{14}C$ at E(t) = 10 MeV has been made by Glover and Jones[51] for the ground state and first three excited states of ^{14}C. Henley and Yu[6] have made DW calculations for the $^{12}C(^3He,n)^{14}O$ reaction at $E(^3He)$ = 20 MeV. Their calculation for the ^{14}C ground state angular distribution fits our data for the analog state at 2.311 MeV in ^{14}N, but predicted relative cross sections for other T = 1 states are much too large, which may be due to the fact that they used an unrealistically small harmonic-oscillator parameter in order to fit the ^{14}O g.s. transition. This was necessary because a pure harmonic oscillator was used without correcting for the exponential decay in the nuclear surface region.

Energy levels of ^{14}N below an excitation energy of 9.0 MeV may be classified into three groups (fig. 3) according to the major configuration of each level. Our group of four positive parity levels are predominatntly of a $(p)^{-2}$ configuration. The ground state and 2.311 MeV state are predominantly $(p1/2)^{-2}$. The other two states of this group have a $(p3/2)^{-1}$ $(p1/2)^{-1}$ configuration. Another group of positive parity levels arise from an $(s,d)^2$ configuration. Some mixing between these two types of positive-parity levels is expected. A third group of levels are of negative parity and arise from a $(p)^{-3}$ (s,d) configuration.

Two sets of wave functions for ^{14}N states have been used in the calculations to be discussed. Cohen and Kurath[14]) have made an intermediate-coupling calculation for nuclei in the p shell. They therefore calculated wave functions only for the four $(p)^{-2}$ states of ^{14}N shown in fig. 3. The ground-state wave function for ^{12}C is also taken from this calculation.

The $(p3/2)^{-n}$ character of the ^{12}C and ^{14}N wave functions will be shown by this work to be important. In addition to ^{14}N states with this major configuration, the ^{12}C ground state, in the Cohen and Kurath[14]) calculations, has a 60% admixture of $(p3/2)^{-n}$ configuration (see table 5 footnote). Of course the Cohen and Kurath calculation neglects any $(s,d)^2$ components in the wave function.

True[13]) has calculated the levels of ^{14}N based upon a model which assumed that ^{14}N consisted of a closed p3/2 core with two particles in the following single-particle states; p1/2, d5/2, 2s1/2, d3/2 and f7/2. True, therefore, does not describe states with major components of $(p3/2)^{-n}$ configurations, neither do these configurations mix into other states. The two lowest $(p)^{-2}$ states, the negative-parity states except for the 8.489 MeV level, and the $(s,d)^2$ states all below 9 MeV excitation energy in ^{14}N are some of the states predicted by True.

Structure factors G_{NLSJT} for both the Cohen and Kurath$^{14)}$ and True$^{13)}$ wave functions were calculated using the methods of Glendenning$^{1)}$. Two-particle coefficients of fractional parentage needed for calculations using the intermediate-coupling calculation were kindly provided by Dr. Kurath$^{14)}$. Harmonic oscillator single-particle radial wave functions were assumed for the two captured nucleons. An oscillator parameter of $\nu = 0.32$ was used for the $(p)^{-2}$ type levels in both calculations in keeping with the value used by True$^{13)}$ in his calculations. A value of $\nu = 0.27$ was used in the $(s,d)^2$ levels and an average value of $\nu = 0.295$ was used for the negative parity levels which was also in keeping with the values used by True.^{13}

The structure factor for the 8.489 MeV state was calculated using the Cohen and Kurath$^{14)}$ ^{12}C ground state and a $(p3/2)^{-1}(p1/2)^2(d5/2)$ configuration$^{31)}$. As was mentioned in sect. 3, a 1^+ T = 0 state predicted by True had been associated with the 9.702 MeV level of this spin and parity assignment. The 10.096 and 10.213 MeV levels have also been tentatively assigned 1^+ T = 0. The structure factors for the state in question are much smaller than those for other $(s,d)^2$ states and on this basis it is not expected that the state should be observed. Of the three levels under discussion only the 10.213-MeV level is not observed and the predicted state is tentatively assigned to this level.

The 10.85 MeV level was also discussed in sect. 3. Two states predicted by True$^{13)}$ may possibly be assigned to this level; a 4^+ T = 0 and a 3^+ T = 0. The spectroscopic factors are vanishingly small for the 3^+ state leaving only the 4^+ state for tentative assignment to the 10.85-MeV level of ^{14}N. The spectroscopic factor for the 4^+ state is larger than the factor for the 5^+ T = 0 giant state seen in (α,d) reactions$^{6,7)}$. If the 10.85 MeV level is to be associated with the 4^+ state predicted by True the strength of this configuration must be mixed into other 4^+ states. Two states near 12.5 MeV excitation are tentatively assigned 4^+. If one of these is a T = 1 state, as discussed in sect. 3, the other could contain part of the strength of the 4^+ state under consideration.

Optical-model parameters used in the DW calculations for the $^{12}C(^3He,p)^{14}N$ reaction are shown in table 3. A Woods-Saxon potential was used with V,W and W_d as the potential depths for the real, volume-imaginary and imaginary-surface-derivative potentials respectively. R_o, R_i and R_c are the real, imaginary and Coulomb radius parameters. A_o and B are the real and imaginary surface-diffusness parameters.

Several sets of parameters obtained from the elastic scattering of ^{3}He on ^{12}C (ref. 11) were used without success in DW calculations. Parameter set 2 yielded a fit to positive-parity states up to about 7.5 MeV excitation energy. It did not, however, yield a fit for odd-parity states. Potential set 1 was constructed by summing the potentials for single nucleons and was found to give reasonable fits to the data. Bjorklund and Fernbach[52] obtained a single set of optical potentials for the scattering of 7 MeV neutrons on targets of mass 27 to 209. Perey[53]) has obtained a systematic set of parameters for proton scattering at energies of 9 to 22 MeV and for targets of mass 27 to 197. It was assumed these systematics would extend to mass 12 and 7 MeV energy. These proton and neutron potentials both used the same radius and diffuseness parameters and were, therefore, used in set 1. The potential well depths of set 1 were obtained by summing the single-nucleon potential depths discussed above.

Proton parameters for the exit channel were obtained by fitting data for proton elastic scattering on ^{14}N. Proton data at 31 MeV taken by Kim et al.[54])

and at 20 MeV taken by Chow and Wright[55]) were fitted using a fixed set of parameters as shown in table 3. Only the real well depth was adjusted as a function of energy. A straight-line interpolation or extrapolation from these two potentials was taken to obtain a potential set for the energy of the outgoing proton. The systematic proton potentials of Perey[53] were also used in a few calculations and were found to give a 1% to 4% change in cross section magnitude and no observable change in calculated angular distribution in comparison to the use of potentials 3 and 4 as discussed.

DW calculations were made using the program REACTION 6 which employs the zero-range and the local-potential approximations. The quantity B_{NL}^{M} is the amplitude for transfer of the pair into the center-of-mass state N,L described as a harmonic oscillator in the interior matched to a Hankel function having the appropriate assumptotic behavior. Sums on M,N,L and J of eq. (2) were calculated by the program. Using dominant N and L value for a given transition, Oak Ridge program JULIE also gave fits to angular distributions. In figs. 4 to 8, DW calculations for levels below 9-MeV excitation are shown as curves normalized to the data. The wave functions of levels at higher excitation energy are uncertain as discussed above, and the binding energy is becoming so small that calculated angular distributions are not meaningful.

Several L = 0 transitions are shown in fig. 4. The general features of the transitions are reproduced although the first maximum is at too large an angle in general. The fit to the 8.617 MeV level is the worst obtained. In this case the first experimental maximum is entirely out of phase with the calculated curve.

A group of L = 1 transitions is shown in fig. 5. These transitions are reasonably well fit to an angle of about 70° center of mass, beyond which the calculations fall below the experimental values.

A group of L = 2 transitions is shown in fig. 6. Note again the contrast between the transitions to two $(p)^{-2}$ type states and the 6.44 MeV state. The calculated curves agree quite well with the g.s. and 7.019 MeV state angular distributions but the calculation for the 6.44 MeV state does not reproduce its more forward peaking. This may suggest that corrections must be made in the calculations for shell effects.

The ground-state transition is allowed by selection rules to have both and L = 0 and an L = 2 component. Examination of the angular distribution indicates that very little L = 0 component is present. The solid-line curve is a calculation based upon the wave functions of Cohen and Kurath[14]). This calculation reproduces the data very well. The dashed line segment is a calculation based upon the wave functions of True[13]). The forward-rising nature of this latter calculation indicates too large an L = 0 component in the True wave function. The source of this error will be further discussed in connection with other calculations.

A group of L = 3 transitions is shown with DW calculations in fig. 7. Note that the 8.489 MeV level is well fit with an L = 3 angular distribution which helps to confirm its assigned configuration.

The angular distributions of fig. 8 arises from three unresolved levels near 9 MeV excitation in ^{14}N. Calculations for all three of these levels have been made, the contributions of each level have been weighted by $(2J_2+1)$ as indicated by eq. (2), and the values summed to give the DW fit to the data. The 3^- level gave the smallest contribution.

Experimental and theoretical relative cross sections integrated between 10° and 70° center of mass are shown in table 4. The factor F at the bottom of the table is a measure of the goodness of fit and is defined as the average value of the greater ratio between experimental relative cross section and calculated relative cross section minus one. For a perfect fit F would be zero. The calculated relative cross sections for four states predicted by Cohen and Kurath14) and the four values for $(s,d)^2$ states predicted by True13) are in good agreement with experiment.

Those states in the True13) calculation which have p character are not in good relative agreement with the experiment. Two cases of disagreement are particularly striking. The experimental ratio of the first excited state to the ground state is 0.8. This ratio is predicted to be 0.7 by the wave functions of Cohen and Kurath14). The wave functions of True13), on the other hand, predict a ratio 0.2. The disagreement in the calculated relative cross section of the 4.9 and 5.10 MeV levels is also striking.

It seems reasonable to postulate that the failure of the calculations based upon True wave functions of p character is due to the fact that these functions do not account for the $(p3/2)^{-n}$ character of these levels. To test this idea further, several model calculations were carried out for the ground state and the 2.311 MeV state of ^{14}N and results are shown in table 5.

Two experimentally observable quantities were examined in the model calculations. One is the ratio between the cross sections to the two states and the other is the ratio of the $L = 0$ to $L = 2$ amplitudes in the ground-state transition. The ground-state angular distribution is sharply falling at small angles. As seen in the case of the 2.311 MeV transition, an $L = 0$ angular distribution is strongly forward peaked. From these two observations it is concluded that the $L = 0$ contribution to the ground state transition is small

It is noted that the Cohen and Kurath wave functions properly account for both of these observables. The calculation in the jj limit gives a poor value for the relative strength of the states. It is important to note that the introduction of the Cohen and Kurath ^{12}C wave function makes a big improvement in the relative strengths of the two states although agreement with experiment is still poor. This improvement is not too surprising when it is noted that the intermediate-coupling wave function of ^{12}C is only 40% closed p3/2 core.

It is seen in table 5 that only 10% of the g.s. and 15% of the first excited state are of components other than $(p1/2)^2$ and yet the consideration of this small admixture makes the pronounced change seen between using the Cohen and Kurath or $(p1/2)^2$ wave functions for ^{14}N with the Cohen and Kurath wave function for ^{12}C. These calculations entirely within the p shell are to be considered quite reliable. This is a case where the coherent and enhancing effects of two-nucleon transfer make the transitions sensitive to the minor components of the wave function.

In all cases where the True$^{13)}$ p-type wave functions were introduced there was not agreement with experiment. However, it was found that in this particular instance, calculations in two different shells were not in proper relative agreement. It cannot, therefore, be concluded that the $(s,d)^2$ admixtures predicted by True are too large. It can be said that the p3/2 hole character in these wave functions is very important and may account for some of the failure in the case of True's p-type states.

6. Summary

Information in three categories has been obtained from this work: 1) spectroscopy 2) wave functions of ^{14}N and 3) stripping reaction mechanism in light nuclei. The following spectroscopic information has been obtained. An L = 3 angular distribution has been observed for the transition to the 8.489 MeV level which was consistent with its $4^{-}0$ spectroscopic assignment and suggested $(p3/2)^{-1}(p1/2)^{2}(d5/2)$ configuration[31]). The $2^{+}0$ 8.979 MeV level[28]) was associated with the first $2^{+}0$ state calculated by True[13]) and the observed cross section was consistent with this assignment. The 9.388 MeV level was restricted to a unique spin and parity of 2^{-}. The 10.213 MeV level was associated with the third $1^{+}0$ state calculated by True[13]) on the bases of its suggested spin and parity and the fact that the level was not observed in either the (α,d)[6,7]) or the (^{3}He,p) reaction. The 10.85 MeV level[6]) was tentatively assigned $4^{+}0$ with a partial amplitude of the first $4^{+}0$ state predicted by True[13]). This suggestion was made on the basis of its observed angular distribution in the (^{3}He,p) reaction and its large cross section in the (α,d) reaction[6,7]).

The above spectroscopic assignments were based in part upon reaction calculations for the (^{3}He,p) reaction using the ^{14}N wave functions and the necessary ^{12}C ground state wave functions taken from the work of Cohen and Kurath[14]) and of True[13]). Relative cross sections to predicted levels were calculated and compared to experimental, relative cross sections. Such comparisons were satisfactory for the four $(p)^{-2}$ states predicted by Cohen and Kurath[14]) and for the states of dominant $(s,d)^2$ configuration predicted by True[13]).

Calculated cross sections for states with p character predicted by True[13]) did not agree with experimental values. This last observation, together with model calculations for the ground state and 2.31 MeV state of ^{14}N indicated that the p3/2 hole character of wave functions with p character must be included. The model calculations just noted were sensitive to 10 or 15 per cent admixtures in the wave functions which demonstrated that the two-nucleon transfer reaction can be sensitive to the details of the wave function.

It was not found necessary to use a spin-dependent potential for the interaction in the distorted-wave theory which is responsible for the nuclear rearrangement. Other work$^{2,3)}$ suggests the need for a spin-dependent potential and indeed from basic considerations one expects it. This important problem, therefore, remains for future solution. Nevertheless, this work has indicated that the two nucleon transfer mechanism is basically understood and applicable in the region of light nuclei.

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References

1) Norman K. Glendenning, Phys. Rev. 137 (1965) B102.

2) D. G. Fleming, J. Cerny, and N. K. Glendenning, Phys. Rev. (to be published).

3) J. C. Hardy and I. S. Towner, Phys. Letters 25B (1967) 98.

4) Gy. Bencze and J. Zimányi, Nucl. Phys. 81 (1966) 76; Norman K. Glendenning, Phys. Rev. 156 (1967) 1344; R. A. Broglia and C. Riedel, Nucl. Phys. A92 (1967) 145; R. M. Drisko and F. Rybicki, Phys. Rev. Letters 16 (1966) 275; G. F. Bertsch, Phys. Letters 25B (1967) 62.

5) Ernest M. Henley and David U. L. Yu, Phys. Rev. 133 (1964) B1445; V. S. Mathur and J. R. Rook, Nucl. Phys. A91 (1967) 305; A. Y. Abul-Magd and M. El-Nadi, Nucl. Phys. 77 (1966) 182; Ching Liang Lin and Shiro Yoshida, Progr. Theoret. Phys. (Kyoto) 32 (1964) 885; Ching Liang Lin,, Progr. Theoret. Phys. (Kyoto) 36 (1966) 251; B. Bayman, Nuclear-Structure Information From Many-Particle Transfer Reactions, in Nuclear Spectroscopy with Direct Reactions II. Proceedings, ed. by F. E. Throw, ANL-6878, March 1964, p. 335; J. R. Rook and D. Mitra, Nucl. Phys. 51 (1964) 96; S. Yoshida, Nucl. Phys. 33 (1962) 685.

6) C. D. Zafiratos, J. S. Lilley, and F. W. Slee, Phys. Rev. 154 (1967) 887; and C. D. Zafiratos (University of Colorado, Boulder) private communication, September, 1966.

7) R. H. Pehl, E. Rivet, J. Cerny and B. G. Harvey, Phys. Rev. 137 (1965) B114.

8) B. G. Harvey, E. J-M. Rivet, A. Springer, J. R. Meriwether, W. B. Jones, J. H. Elliott, and P. Darriulat, Nucl. Phys. 52 (1964) 465.

9) F. S. Goulding, D. A. Landis, J. Cerny, and R. H. Pehl, Nucl. Instr. Methods 31 (1964) 1; F. S. Goulding, D. A. Landis, J. Cerny and R. H. Pehl, IEEE (Inst. Elec. Electron Engrs.) Trans. Nucl. Sci. 13, No. 3 (1966) 514.

10) Differential cross sections are tabulated in the Appendix ref. 11.

11) Nolan F. Mangelson, The (^{3}He,p) and (α,d) Two-Nucleon Stripping Reactions on ^{12}C and ^{16}O: Mechanism and Nuclear Spectroscopy (Ph.D Thesis), University of California, Berkeley, UCRL-17732, August 1967.

12) T. Lauritsen, F. Ajzenberg-Selove, Nuclear Data Sheets, ed. by K. Way et al. (Printing and Publishing Office, National Academy of Sciences--National Research Council, Washington, D. C., 1962), NRC 61-5,6.

13) William W. True, Phys. Rev. 130 (1963) 1530; and W. W. True (University of California, Davis, California), private communication to N. K. Glendenning (Lawrence Radiation Laboratory, Berkeley, California).

14) S. Cohen and D. Kurath, Nucl. Phys. 73 (1965) 1; and D. Kurath, Argonne National Laboratory, Argonne, Illinois, private communications, May and July, 1966.

15) E. K. Warburton and W. T. Pinkston, Phys. Rev. 118 (1960) 733.

16) I. Talmi and I. Unna, Ann. Rev. Nucl. Sci. 10 (1960) 353.

17) G. C. Ball and J. Cerny, Phys. Letters 21 (1966) 551.

18) C. H. Holbrow, R. Middleton, J. Parks, and J. Bishop, in Nuclear Spin-Parity Assignments, ed. by N. B. Gove and R. L. Robinson (Academic Press, New York, 1966) p. 354.

19) J. H. Manley, Phys. Rev. 130 (1963) 1475.

20) D. A. Bromley, E. Almqvist, H. E. Gove, A. E. Litherland, E. B. Paul, and A. J. Ferguson, Phys. Rev. 105 (1957) 957.

21) S. Gorodetzky, R. M. Freeman, A. Gallmann, and F. Haas, Phys. Rev. 149 (1966) 801.

22) Gordon C. Ball and Joseph Cerny, Phys. Rev. 155 (1967) 1170.

23) C. H. Holbrow, R. Middleton, and B. Rosner, Phys. Rev. 152 (1966) 970.

24) H. J. Rose, W. Trost and F. Riess, Nucl. Phys. 44 (1963) 287.

25) J. O. Newton, R. S. Blake, D. J. Jacobs and J. P. Shapira, Nucl. Phys. 71 (1965) 113.

26) E. K. Warburton, J. S. Lopes, R. W. Ollerhead, A. R. Poletti, and M. F. Thomas, Phys. Rev. 138 (1965) B104.

27) C. P. Swann, Phys. Rev. 148 (1966) 1119.

28) V. A. Latorre and J. C. Armstrong, Phys. Rev. 144 (1966) 891.

29) D. E. Alburger, A. Gallmann, J. B. Nelson, J. T. Sample, and E. K. Warburton, Phys. Rev. 148 (1966) 1050.

30) R. N. Glover and A. D. W. Jones, Nucl. Phys. 84 (1966) 673.

31) R. W. Detenbeck, J. C. Armstrong, A. S. Figuera, and J. B. Marion, Nucl. Phys. 72 (1965) 552.

32) R. R. Carlson, Phys. Rev. 148 (1966) 991.

33) F. Riess and W. Trost, Nucl. Phys. 78 (1966) 385.

34) B. G. Harvey, J. Cerny, R. H. Pehl, and E. Rivet, Nucl. Phys. 39 (1962) 160.

35) E. Rivet, R. H. Pehl, J. Cerny, and B. G. Harvey, Phys. Rev. 141 (1966) 1021.

36) M. W. Sachs, C. Chasman, and D. A. Bromley, Phys. Rev. 139 (1965) B92.

37) H. J. Rose, F. Riess and W. Trost, Nucl. Phys. 52 (1964) 481.

38) E. Kashy, R. R. Perry, R. L. Steele, and J. R. Risser, Phys. Rev. 122 (1962) 884.

39) L. J. Parish, J. A. Rawlins, and Y. M. Shin, Bull. Am. Phys. Soc. 11 (1966) 27.

40) J. R. Priest, D. J. Tendam, and E. Bleuler, Phys. Rev. 119 (1960) 1295.

41) E. J-M. Rivet, Investigation of Highly Populated Levels of the $(d5/2)^2_5$ and $(f7/2)^2_7$ Configurations of the (α,d) Reaction, UCRL-11341, March 1964; and private communications, 1965.

42) S. Hinds and R. Middleton, Proc. Phys. Soc. (London) 75 (1960) 745.

43) H. W. Fulbright, W. Parker Alford, O. M. Bilaniuk, V. K. Deshpande, and J. W. Verba, Nucl. Phys. 70 (1965) 553.

44) D. R. Osgood, J. R. Patterson, and W. E. Titterton, Nucl. Phys. 60 (1964) 503.

45) V. K. Deshpande, H. W. Fulbright and J. W. Verba, Nucl. Phys. 52 (1964) 457.

46) S. Hinds and B. M. Hinds, Nucl. Phys. 48 (1963) 690.

47) J. H. Manley and W. E. Stein, Phys. Rev. 144 (1966) 956.

48) S. K. Penny and G. R. Satchler, Nucl. Phys. 53 (1964) 145; Seldon Keith Penny, Inelastic Effects in Stripping and Other Direct Reactions (Ph.D. Thesis), University of Tennessee (1966); B. Kozlowsky and A. De-Shalit, Nucl. Phys. 77 (1966) 215; F. S. Levin, Phys. Rev. 147 (1966) 715; P. J. Iano and N. Austern, Phys. Rev. 151 (1966) 853.

49) B. G. Harvey, J. R. Meriwether, J. Mahoney, A. Bussiere de Nercey, and D. J. Horen, Phys. Rev. 146 (1966) 712; P. H. Stelson and L. Grodzins, Nucl. Data A-1 (1965) 21.

50) F. Pühlhofer and R. Bock, Phys. Letters 25B (1967) 117.

51) R. N. Glover, and A. D. W. Jones, Nucl. Phys. 81 (1966) 277.

52) F. Bjorklund and S. Fernbach, Phys. Rev. 109 (1958) 1295.

53) F. G. Perey, Phys. Rev. 131 (1963) 745.

54) C. C. Kim, S. M. Bunch, D. W. Devins and H. H. Forster, Nucl. Phys. 58 (1964) 32.

55) R. H. Chow and B. T. Wright, Can. J. Phys. 35 (1957); R. H. Chow, Absolute Angular Distributions of 20 MeV Protons Elastically Scattered by Oxygen and Nitrogen (Ph.D. Thesis) University of California, Los Angeles, May 1955.

Table 1. Nitrogen 14: energy levels and cross sections for $^{12}C(^{3}He,p)^{14}N$ at $E(^{3}He)$ = 20 MeV.

Experimental		This Work			Dominant Configurations	References[b]
Energy (MeV)	J^{π} T	Energy (MeV ±	keV)	σ^{a} (mb)		
0.0	1^{+} 0	0.0	19	0.96	$0.975(p1/2)^{2} - 0.208(p3/2,p1/2)^{-1}$	6,7,14-17
					$-0.951(p1/2)^{2} - 0.217(d5/2)^{2}$	13
2.311	0^{+} 1	2.31	22	0.77	$0.914(p1/2)^{2} - 0.405(p3/2)^{-2}$	6,7,14-17 18-23
					$-0.931(p1/2)^{2} + 0.298(d5/2)^{2}$	13
3.945	1^{+} 0	3.94	32	1.41	$0.932(p3/2,p1/2)^{-1} - 0.318(p3/2)^{-2}$	6,7,14-18,21, 23
4.910	0^{-} 0	4.93	33	1.34	1.00 (p1/2,s1/2)	6,7,13,15,16, 18,21,23-25
5.104	2^{-} 0	5.12	36	3.35	0.960(p1/2,d5/2) - 0.220(d3/2,f7/2)	6,7,13,15,16 18,21,23-25
5.685	1^{-} 0	5.65	30	1.84	0.985(p1/2,s1/2) + 0.140(p1/2,d3/2)	6,7,13,15,16 18,21,23-25
5.832	3^{-} 0	5.84	30	1.58	0.989(p1/2,d5/2) - 0.120(d3/2,f7/2)	6,7,13,15,16 18,21,23,24
6.21	1^{+} 0	6.21	20	2.83	$0.834(s1/2)^{2} + 0.365(d3/2,d5/2) + 0.348(d5/2)^{2}$	6,7,13,15,16 21
6.44	3^{+} 0	6.46	18	10.80	$0.810(s1/2,d5/2) + 0.440(d5/2)^{2}$	6,7,13,15,21
7.029	2^{+} 0	7.01	42	0.84	$1.000(p3/2,p1/2)^{-1}$	6,7,14-17 21,26,27
7.97	2^{-} 0	7.95	26	0.91	-0.980(p1/2,d3/2) - 0.160(d5/2,f7/2)	6,7,13,15
8.060	1^{-} 1	8.05	35	0.70	-0.987(p1/2,s1/2) + 0.132(p1/2,d3/2)	6,7,13,15,16 22,28-30

Table 1. (continued)

Experimental			This Work			Dominant Configurations	References[b]
Energy (MeV)	J^{π}	T	Energy (MeV ±	keV)	σ[a] (mb)		
8.489	4^-	0	8.47	30	1.82	$(p3/2)^{-1}(p1/2)^{2}(d5/2)$	6,7,15,31,32
8.617	0^+	1	8.61	34	0.68	$-0.907(s1/2)^{2} - 0.308(d5/2)^{2}$	6,13,15,16 22,28,29
8.71	0^-	1				1.000(p1/2,s1/2)	13,15,16,22 28-30,33
8.906	3^-	1				-0.994(p1/2,d5/2) - 0.086(d5/2,f7/2)	13,15,16,22 28-30
8.963	5^+	0	8.96	19	15.88	$-0.995(d5/2)^{2} + 0.098(f7/2)^{2}$	6,7,13,31,32 34-36
8.979	2^+	0				-0.850(s1/2,d5/2) + 0.420(s1/2,d3/2)	13,15,28
9.129	2^-	0	9.15	18	3.64	$(p3/2)^{-1}(p1/2)^{2}(s;d)$	6,31
9.17	2^+	1				$\approx 0.7(s1/2,d5/2), \approx 0.7(p3/2,p1/2)^{-1}$	6,13-15,17 22,30,32,37
9.388	2^-	0[c]	9.39	26	2.71		6,7,15,28
9.508	2^-	1				-0.999(p1/2,d5/2) + 0.026(p1/2,d3/2)	6,7,13,15,16 22,28-30
9.702	1^+	0	9.70	22	1.56		6,7,15,28
10.096	(1^+)	0	10.08	18	1.63		6,7,15,28,38
10.213	1^+	(0)[c]				$0.695(d5/2)^{2} - 0.532(s1/2)^{2}$	13,15,24,28
10.431	2^+	1	10.43	20	2.76	$\approx 0.7(s1/2,d5/2), \approx 0.7(p3/2,p1/2)^{-1}$	6,7,13-17,22, 28,30,37
10.55	(1^-)		10.56	28	0.56		6,38
10.85	(4^+)	0[c]	10.81	23	1.01	0.770(d3/2,d5/2) + 0.640(p1/2,f7/2)	6,7,13

Table 1. (continued)

Experimental		This Work			Dominant Configurations	References[b]
Energy (MeV)	J^{π} T	Energy (MeV	± keV)	σ^a (mb)		
11.06	1^+ 0	11.06	50	0.98		6,7
11.23	(3^-)1	11.27	50			6,38
11.299	2^- 0					6,28
11.39	(1^+)0	11.39	40			38
11.51	3^+ 0	11.51	30			6
11.66		11.66	40			
11.74	1^+	11.79	110			
11.80	(2^+)					
11.97	(2^+)	11.95	30			
12.05						
12.21	3^-					
12.29						
12.41	4^- 0	12.40	30	3.41		6,7
12.52		12.50	20	2.18		
12.61	3^+	12.63	25	1.51		
12.69	3^-	12.74	30	8.90		
12.80	4^+					
12.83	4^- 0					6,7,36
12.95	(4^+)	12.90	25	5.74		
(13.05)	(0)					6

Table 1. (continued)

Experimental			This Work			Dominant Configurations	References[b]
Energy (MeV)	J^π	T	Energy (MeV	± keV)	σ^a (mb)		
13.17	$0^-,1^-$	0	13.15	40			6
13.72	1^+	1				$(p3/2,p1/2)^{-1}$	17
14.84		0	14.91	60			39
15.5	(6^-)	0	15.8	200		(d5/2,f7/2)	7,13,36,39
16.3		0					39
17.3		0	17.4	200			7,36,39

[a] Total cross section integrated between 10° and 70° center of mass.

[b] References used other than 12.

[c] J^π and/or configuration proposed by this work.

Table 2. Determination of spin dependence by the Hardy and Towner method[a] using the $^{12}C(^3He)^{14}N$ reaction.

Calculation	R(S)	$E(^3He)$ (MeV)
Pure LS $^{12}C_{g.s.}$ and Cohen and Kurath[b] ^{14}N states[a]	0.5	20.1
Cohen and Kurath $^{12}C_{g.s.}$ and ^{14}N states	4.4	10.14[c]
	1.4	13.9[d]
	1.1	20.1
	0.7	31.2[e]

[a] ref. 3

[b] ref. 14

[c] ref. 42

[d] ref. 40

[e] ref. 41

Table 3. Optical-model parameters for the $^{12}C(^{3}He,p)^{14}N$ reaction.

Particle	Target	Set	V (MeV)	R_o (F)	A_o (F)	W (MeV)	W_d (MeV)	R_1 (F)	B (F)	R_c (F)
^{3}He(20 MeV)	^{12}C	1	146.5	1.25	.65		36.5	1.25	.47	1.25
"	"	2	220.0	1.16	.597	12.4		1.55	1.046	1.3
p(30 MeV)	^{14}N	3	42.0	1.25	.65		6.0	1.25	.50	1.25
p(20 MeV)	"	4	47.0	1.25	.65		6.0	1.25	.50	1.25

Table 4. Cross section ratios for the reaction $^{12}C(^3He,p)^{14}N$ at $E(^3He)$ = 20 MeV: experiment and theory compared.

Level (MeV)	Major L	Relative Level Cross Sections[a]			
		Experiment	Cohen and Kurath[b]	True[b]	
			(p^2)	(s,d)	(p^2) + (p)(s,d)
0.0	2	1.0	1.1		1.0
2.311	0	0.8	0.8		0.3
3.945	0	1.5	1.4		
4.91	1	1.4			0.7
5.10	1	3.5			0.7
5.69	1	1.9			1.6
5.83	3	1.6			2.6
6.21	0	3.0		2.8	
6.44	2	11.3		12.4	
7.029	2	0.9	0.6		
7.97	3	1.0			2.3
8.06	1	0.7			0.7
8.489	3	1.9			1.0[d]
8.617	0	0.7		0.6	
8.71	forbidden				
8.906	3[c]	16.6		11.6	
8.963	4				
8.979	2				
			F^e = 0.2	0.2	1.1

[a] Cross sections integrated from 10° to 70° center of mass. Each column independently normalized.

[b] References for wave functions used are as follows: True[13]) and Cohen and Kurath[14]).

[c] These three states are unresolved by the experiment.

[d] This level was assumed to be $(p3/2^{-1},d5/2)_{4^-}$ coupled to Cohen and Kurath wave function for ^{12}C.

[e] Goodness of fit parameter defined in the text.

Table 5. Model calculations for g.s. $(1^+,0)$ and 2.311 MeV $(0^+,1)$ states of ^{14}N.

^{14}N Wave Function[a] ^{12}C Wave Function	Experiment	C & K C & K	True $(p1/2)^0$	$(p1/2)^2$ $(p1/2)^0$	$(p1/2)^2$ C & K	True C & K	Combined[c] C & K
$\frac{\text{Cross Section (2.311)}^b}{\text{Cross Section (g.s.)}}$	0.8	0.7	0.2	0.2	0.5	0.4	0.6
$\frac{\text{Cross Section (L=0,g.s.)}}{\text{Cross Section (L=2,g.s.)}}$	small	0.06	0.3	0.07	0.2	0.4	0.3
Cross Section (Relative,g.s.)	-	7.2	32.0	14.8	7.1	22.6	18.8

[a] $\Psi(14,g.s.) = -0.951\ (p1/2)^2 - 0.217\ (d5/2)^2 + \text{-----}$ (True) [13]

$= 0.975\ (p1/2)^2 - 0.208\ (p1/2)^3 - 0.076\ (p1/2)^4$ (Cohen & Kurath) [14]

$\Psi(14,2.311) = -0.931\ (p1/2)^2 + 0.299\ (d5/2)^2 + \text{-----}$ (True)

$= 0.914\ (p1/2)^2 - 0.405\ (p1/2)^4$ (Cohen & Kurath)

$\Psi(12,g.s.) = 0.612\ (p1/2)^0 + 0.261\ (p1/2)^2_A + 0.625\ (p1/2)^2_B + 0.255\ (p1/2)^3 + 0.319\ (p1/2)^4$ (Cohen & Kurath)

[b] Cross sections integrated over 10° to 70°.

[c] True wave functions with the C & K wave functions replacing the $(p1/2)^2$ configurations. This procedure was suggested by E. K. Warburton.

Figure Captions

Fig. 1. Proton energy spectrum for the $^{12}C(^{3}He,p)^{14}N$ reaction at $E(^{3}He)$ = 20.1 MeV.

Fig. 2. Proton angular distributions for transitions to the ^{14}N ground state via a $^{12}C(^{3}He,p)^{14}N$ reaction at various energies; 5.98 , 9.37 and 10.14 MeV data by Hinds and Middleton$^{42)}$; 13.9 MeV data by Priest et al.$^{40)}$; 20.1 MeV data by this work; 31.2 MeV data by Rivet$^{41)}$.

Fig. 3. ^{14}N energy levels below 9-MeV excitation grouped according to major configuration. References are listed in table 1.

Fig. 4. Proton angular distributions for the $^{12}C(^{3}He,p)^{14}N$ reaction at $E(^{3}He)$ = 20.1 MeV; transitions of predominant $L \doteq 0$ character. The solid-line curves are DW calculations. Statistical errors are indicated by error bars or are smaller than the point symbols.

Fig. 5. Proton angular distributions for transitions of predominant L = 1 character. See caption of fig. 4.

Fig. 6. Proton angular distributions for transitions of predominant L = 2 character. The solid-line curve of the g.s. transition is calculated using the Cohen and Kurath$^{14)}$ wave functions--the broken-line segment is calculated using True$^{13)}$ wave functions. See caption of fig. 4.

Fig. 7. Proton angular distributions. The first three distributions are of predominant L = 3 character. The fourth distribution may be an L = 4 transition. See caption of fig. 4.

Fig. 8. Proton angular distribution for a composite peak containing transitions to the 8.906-, 8.963- and 8.979-MeV levels of ^{14}N. See caption of fig. 4.

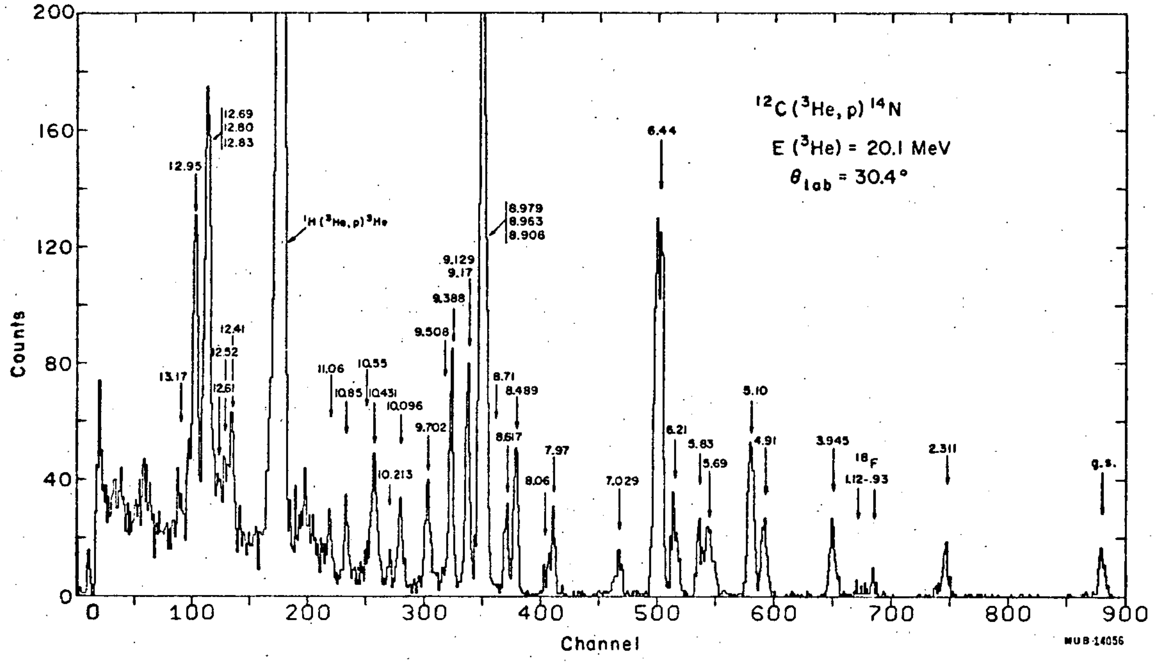

$^{12}C(^{3}He, p)^{14}N$
$E(^{3}He) = 20.1$ MeV
$\theta_{lab} = 30.4°$
Counts
0
40
80
120
160
200
Channel
0
100
200
300
400
500
600
700
800
900
13.17
12.95
12.69
12.80
12.83
12.41
12.52
12.61
$^{1}H(^{3}He, p)^{3}He$
11.06
10.85
10.55
10.431
10.096
10.213
9.702
9.508
9.388
9.129
9.17
8.979
8.963
8.906
8.71
8.489
8.617
8.06
7.97
7.029
6.44
6.21
5.83
5.69
5.10
4.91
3.945
^{18}F
1.12-.93
2.311
g.s.
MUB-14056

Fig. 1

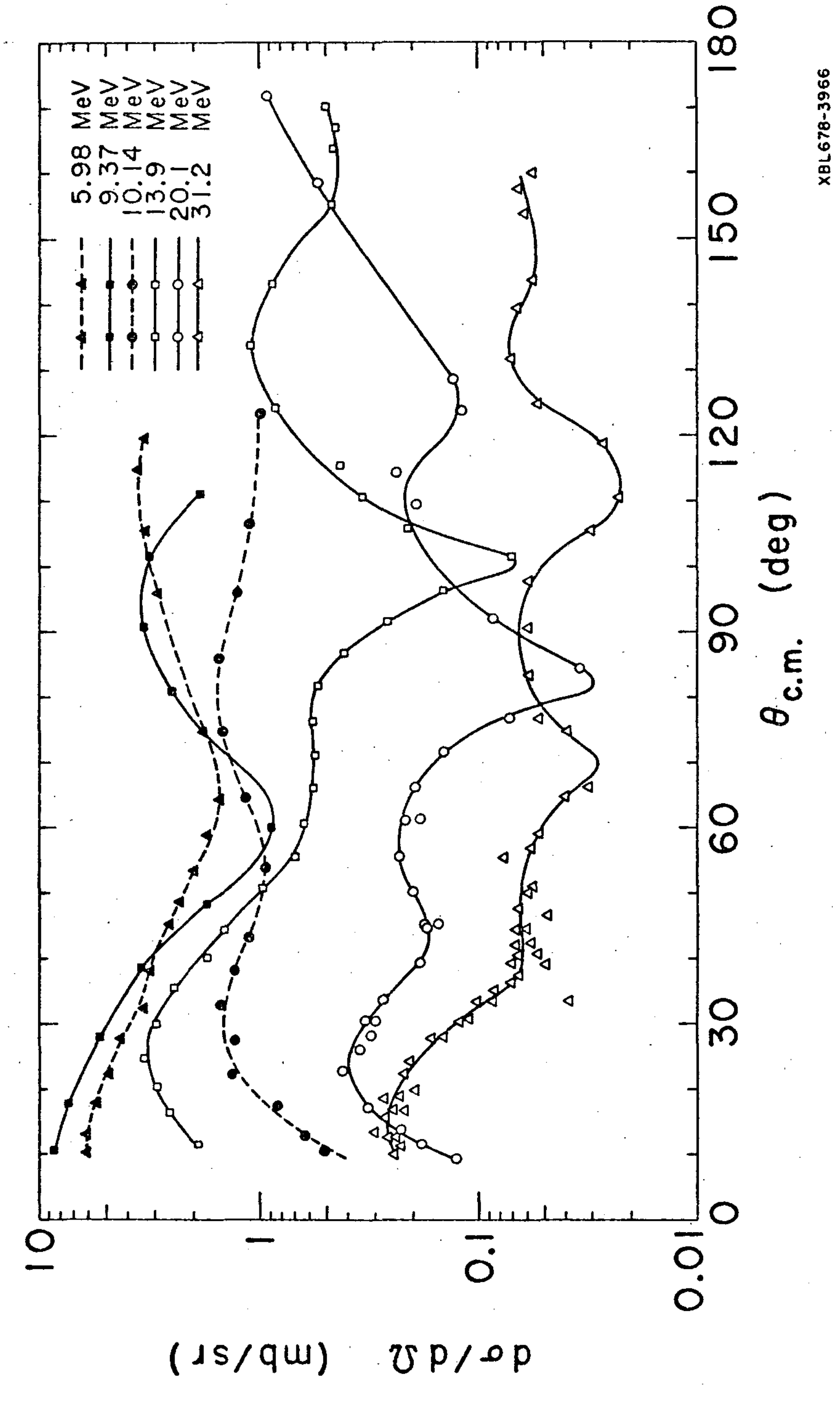

5.98 MeV
9.37 MeV
10.14 MeV
13.9 MeV
20.1 MeV
31.2 MeV
10
1
0.1
0.01
dσ/dΩ (mb/sr)
0
30
60
90
120
150
180
$\theta_{c.m.}$ (deg)
XBL678-3966

Fig. 2

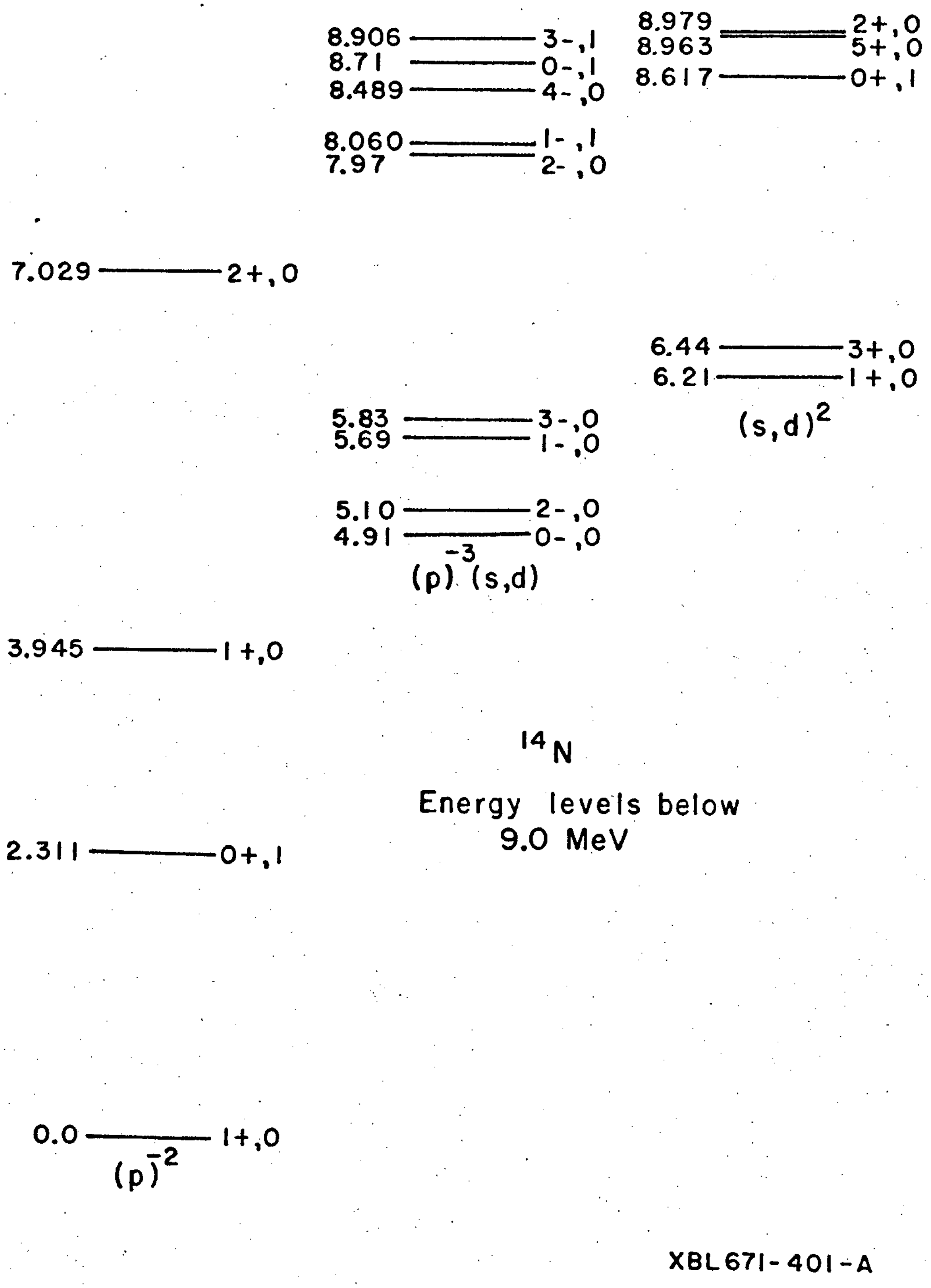
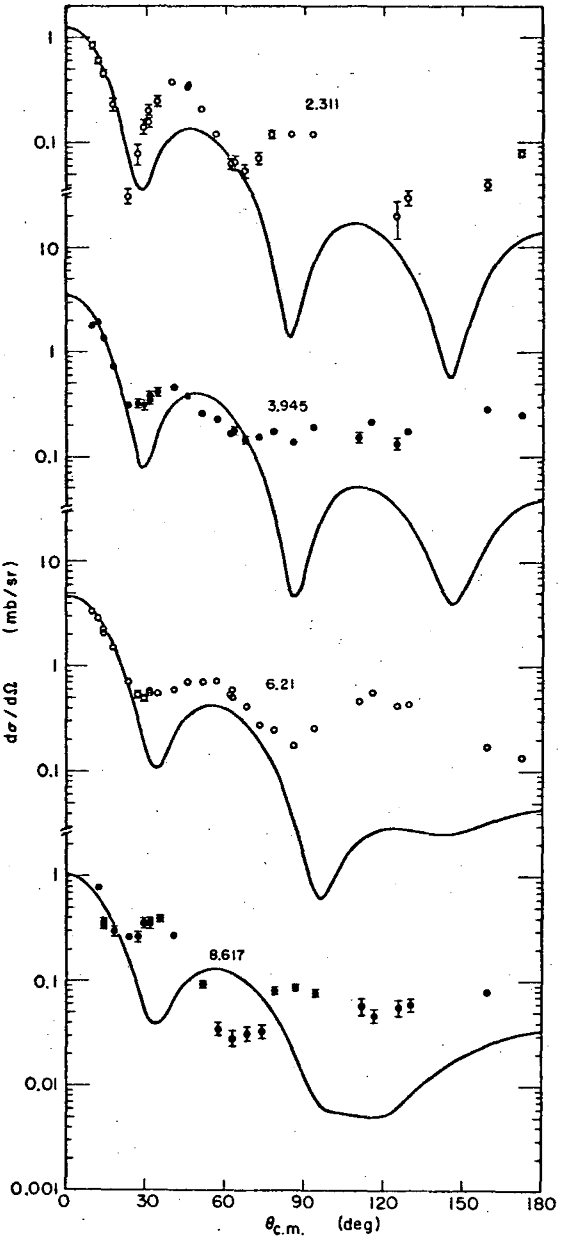
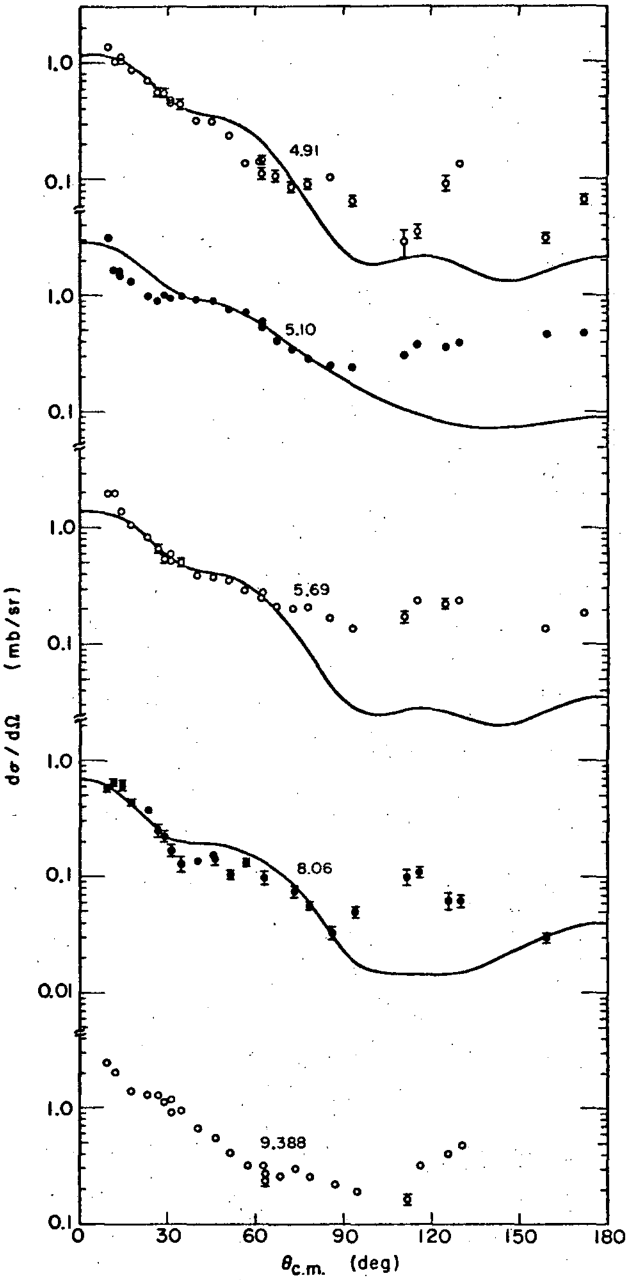

8.906 3-,1
8.71 0-,1
8.489 4-,0
8.060 1-,1
7.97 2-,0
8.979 2+,0
8.963 5+,0
8.617 0+,1
7.029 2+,0
6.44 3+,0
6.21 1+,0
$(s,d)^2$
5.83 3-,0
5.69 1-,0
5.10 2-,0
4.91 0-,0
$(p)^{-3}(s,d)$
3.945 1+,0
^{14}N
Energy levels below 9.0 MeV
2.311 0+,1
0.0 1+,0
$(p)^{-2}$
XBL671-401-A

Fig. 3


dσ/dΩ (mb/sr)
θc.m. (deg)
2.311
3.945
6.21
8.617
1
0.1
10
0.01
0.001
0
30
60
90
120
150
180

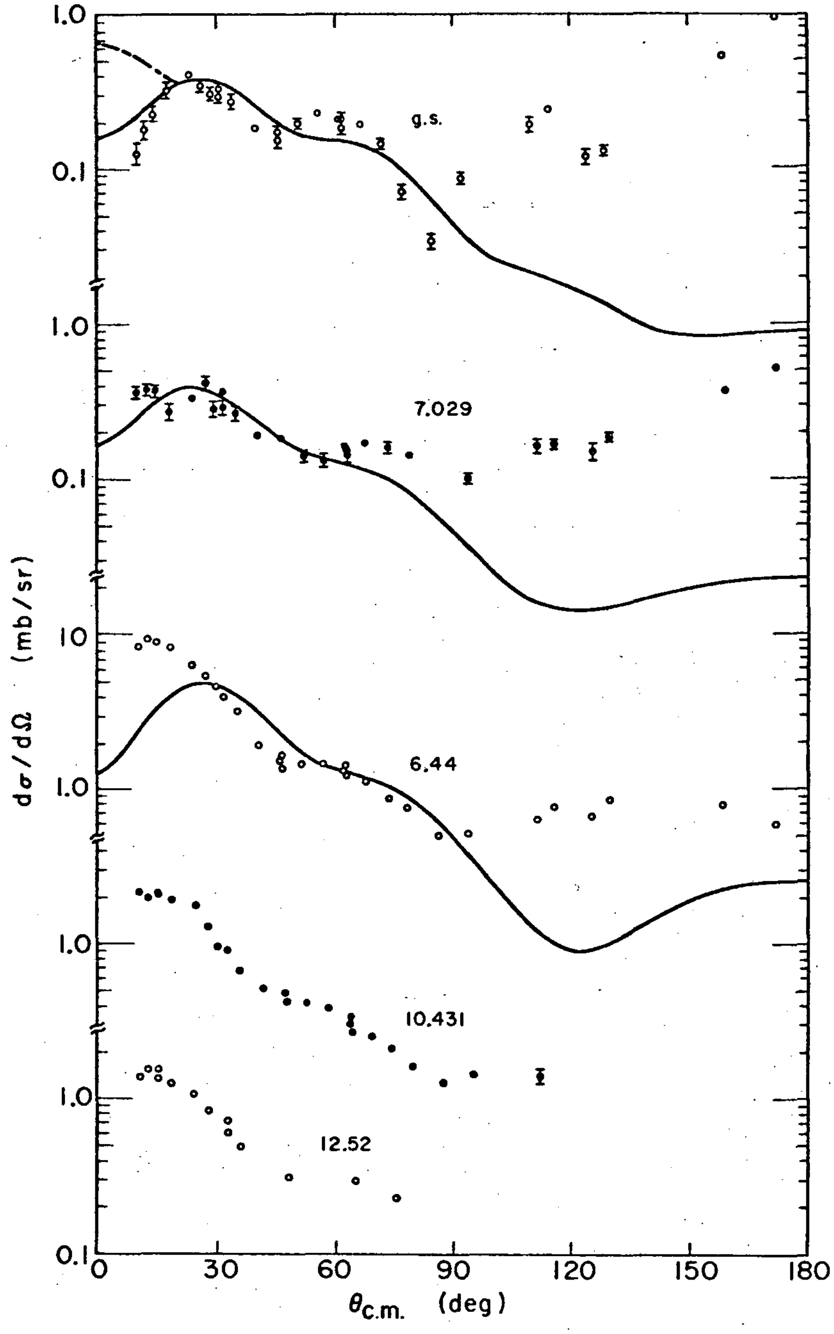
MUB-14357

Fig. 4



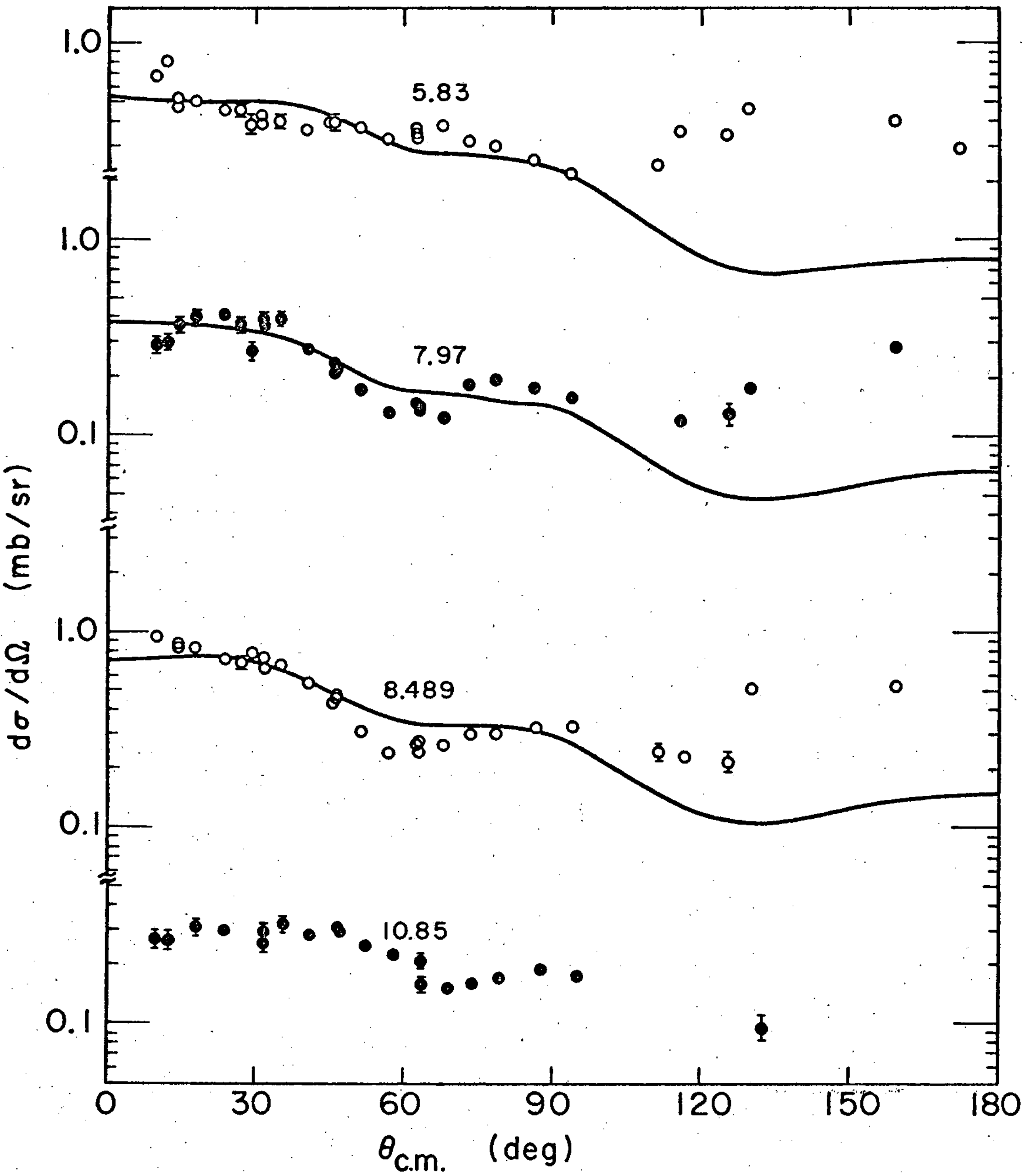
dσ / dΩ (mb/sr)
θc.m. (deg)
4.91
5.10
5.69
8.06
9.388
1.0
0.1
0.01
0
30
60
90
120
150
180
MUB 14058

Fig. 5



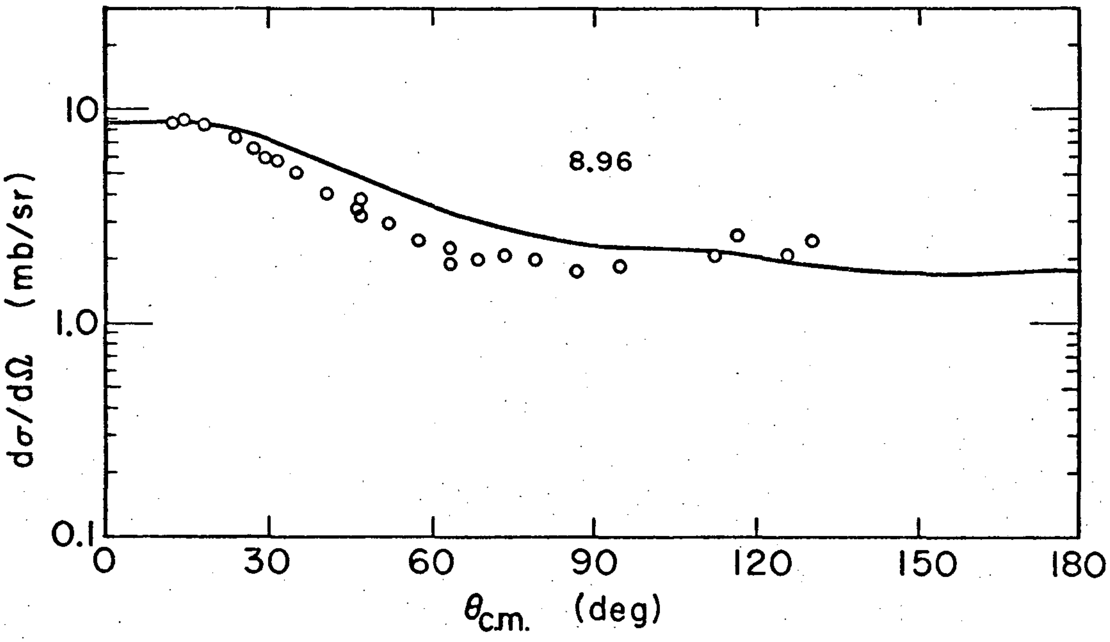
MUB 14054

Fig. 6



MUB-14055

Fig. 7



MUB-14053

Fig. 8