Energy Levels of ^{16}N from the Reaction ^{18}O(d, α)^{16}N†

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Energy levels of ^{16}N have been studied with the ^{18}O(d,α)^{16}N reaction at deuteron energies of 4.75 to 11.5 MeV. No evidence was found for levels between 0.4- and 3.3-MeV excitation energy. Eleven levels were identified or tentatively identified between excitation energies of 8.4 and 10.3 MeV in addition to 32 previously observed levels below an excitation energy of 8.4 MeV. The fourth, sixth, and seventh excited states at 3.36, 3.96, and 4.32 MeV appear to be populated partially via a two-nucleon pickup reaction at E_d = 10.0, 10.6, and 11.2 MeV; and tentative L values are obtained.

I. INTRODUCTION

The nuclei of mass 16, especially ^{16}O, have been the subject of considerable experimental and theoretical interest,[1] because the doubly closed shells of the ^{16}O ground state greatly simplify the theoretical calculations. Experimental studies of the ^{16}O nucleus have determined many $T=0$ levels; however, only a very few levels have been identified as $T=1$. In contrast, the less extensively studied ^{16}N and ^{16}F nuclei, which have no $T=0$ states, should unambiguously determine the $T=1$ states at least up to the lowest $T=2$ state[2,3] which has been reported at 9.9 MeV in ^{16}N and 22.9 MeV in ^{16}O.

Of the two $T=1$ nuclei, ^{16}N is the more accessible to experimental study because of the existence of a variety of possible charged-particle reactions with reasonable Q values. In spite of this fact, the levels of ^{16}N had not been extensively studied when this experiment was begun. The 1962 compilation of Lauritsen and Ajzenberg-Selove[1] indicates a negative-parity ground-state quartet followed by a gap from 0.396 to 3.34 MeV, then a group of levels extending up to 5.53 MeV followed by another gap ending with the 11.62-MeV level which was observed as a ^{14}C(d,n)^{15}N resonance by Chiba.[4] With the exception of the ^{14}N(t,p)^{16}N results of Silbert, Jarmie, and Smith[5] which were obtained for E_t = 2.6 MeV, most of these results were obtained with[6-8] the ^{15}N(n,n)^{15}N and[9] the ^{15}N(d,p)^{16}N reactions, which would be expected to populate primarily one-particle, one-hole configurations. This experimental situation leaves several areas of interest open for study. First, the gap between 5.53- and 11.62-MeV excitation in ^{16}N corresponds to a range of 18.3 to 24.4 MeV in ^{16}O which includes many of the states of interest in the giant dipole resonance in ^{16}O. Second, the recent calculations by Eisenberg and co-workers[10,11] indicate on the order of ten even-parity states of predominantly 2p-2h configurations below 3.5 MeV in ^{16}N. Such configurations would be expected to be best populated by two-nucleon-transfer reactions. Previous experiments have reported no levels in this region except for the ground-state quartet and tentatively identified levels at 1.29, 1.73, and 2.15 MeV. Bonner *et al.*[12] reported levels at 1.29 and 1.71 MeV in the ^{19}F(n, α)^{16}N reaction, but later[13] attributed the observed groups to instrumental effects. However, they had also reported[12] possible analog states in ^{16}F from ^{14}N(^{3}He,n)^{16}F threshold measurements. States at 1.737 and 2.150 MeV were reported[14] as preliminary results in a study of the ^{15}N(d,p)^{16}N reaction by Hallock, Enge, and Sperduto. But as yet none of these levels has received experimental confirmation.

Recent results from the ^{15}N(n,n)^{15}N reaction[15] and the ^{14}N(t,p)^{16}N reaction[16] have extended the range of observed levels for both reactions to 8.37-MeV excitation energy. The results of Hewka, Holbrow, and Middleton also exhibit a few spectra from the ^{15}N(d,p)^{16}N and ^{18}O(d, α)^{16}N reactions which were used primarily to confirm the levels observed in the ^{14}N(t,p)^{16}N data. Other recent results include studies of the ^{14}C(^{3}He,p)^{16}N reaction[17-19] for states up to 5.23-MeV excitation and the ^{10}B(^{7}Li,p)^{16}N and ^{11}B(^{6}Li,p)^{16}N reactions[20] which identify new levels at 8.83 and 9.47 MeV. While all these results tend to cast doubt upon the existence of states between 0.4 and 3.3 MeV, they also produce conflicting spin-parity assignments, especially for the 3.52- and 3.96-MeV states. The present study of the ^{18}O(d, α)^{16}N reaction attempts to provide more information about these low-lying states, and also extends the range of observed levels up to 10.3-MeV excitation.

II. EXPERIMENTAL PROCEDURE

A. Apparatus

Deuterons of various energies from 4.75 to 11.5 MeV produced by a tandem Van de Graaff and were used to bombard a target of gaseous O_2 enriched to 96% ^{18}O. Since ^{18}O is rather expensive, a smallvolume system was required. The gas was contained in a 32-mm-diam cylindrical gas cell with a 1250–12 500-Å-thick nickel foil window which extended over slightly more (205°) than a hemicylinder. For a typical foil thickness of 2500 Å and operating pressures of 25–30 mm Hg there was a decrease of ^{18}O partial pressure, due to leaks and contamination buildup, of less than 6% in 48 hours. The cell was placed in the center of a scattering chamber built by Silverstein,[21] and was connected to an external gas supply and a Texas Instruments Fused Quartz Precision Pressure Gage.

The scattered particles were collimated by a circular slit system with an acceptance angle of 3.3°. This relatively large angle was the primary factor in determining the experimental resolution of 70-100 keV and was used in order to obtain a larger counting rate than would have been possible with better resolution. The particles were detected by a silicon-detector telescope composed of a 37-μ ΔE detector followed by an E detector. The signals from the two detectors were added to provide a total energy signal which was analyzed with a 1024-channel analyzer. In order to eliminate protons, deuterons, and tritons from the spectra, a coincidence condition required at least 2.5 MeV to be lost in the ΔE detector. This energy is 100 keV more than the maximum triton loss in the detector and thus this condition provides the desired discrimination, while allowing α particles of up to 17 MeV to be accepted. The resulting spectrum was composed almost exclusively of α particles with the exception of three or four ^3He, ^6Li, and ^7Li groups which were observed for deuteron energies above 9 MeV.

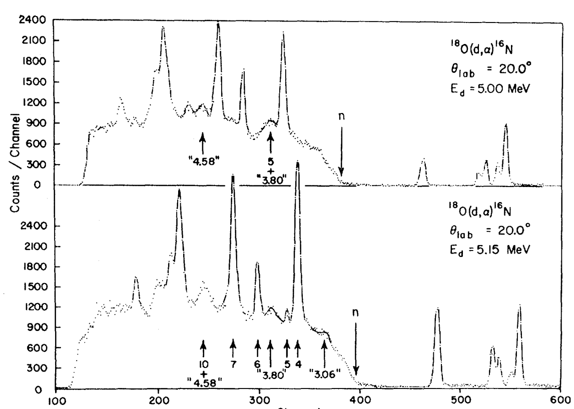

FIG. 1. Typical spectra for $E_d \approx 5.0$ MeV. The arrow labeled "n" indicates the neutron emission threshold. A few ^{16}N excited states are indicated by numbered arrows. The groups labeled "3.06," and "4.58" are discussed in Sec. III. B.

B. Data Collection and Reduction

After preliminary survey data at angles of 32 and 165° for deuteron energies from 5.0 to 11.0 MeV in 250-keV steps failed to give any evidence of ^{16}N states other than the ground-state quartet below 3-MeV excitation, attention was focused on two energy regions: $E_d = 4.75–5.3$ MeV and $E_d = 10.0–11.5$ MeV. The first region was studied for lab angles of 20 to 61° and for 50-keV energy steps in order to make positive identification of several groups which were observed in the range of 3- to 5-MeV excitation energy. As will be discussed later, the groups of interest were found to be from the α decay of ^{19}F states populated by the $^{18}O(d, n)^{19}F^*$ reaction. The second energy region was studied in order to satisfy the other objectives of the experiment, namely, to identify levels of higher excitation, and to study the spin and parity of any groups which might by populated by a direct-reaction mechanism. To this end, an excitation function at a lab angle of 32.4° was measured for energies of 9.8 to 11.5 MeV in 100-keV steps and angular distributions were obtained at deuteron energies of 10.0, 10.6, and 11.2 MeV.

Figures 1 and 2 show spectra typical of the data obtained for deuteron energies of approximately 5 and 10–11 MeV, respectively. The most prominent feature of the spectra is the background below the majority of the peaks. This background arises because ^{16}N becomes unbound with respect to neutron emission at an excitation energy of 2.487 MeV.[22] Therefore, all excited states with greater excitation energies will sit on a three-body continuum from the $^{18}O(d, \alpha n)^{15}N$ reaction. While this background hardly hinders the identification of new levels except to the extent that it conceals small groups, it is a major problem to be reckoned with in extracting differential cross sections.

C. Background

In deciding what portion of the spectrum is to be considered as yield, characteristic of levels in ^{16}N, the first approach is to consider the background to be determined by the available phase space. Any deviations from the phase-space factor are then considered as representative of two-particle final-state interactions with those interactions between neutrons and ^{15}N being characteristic of resonant levels of ^{16}N. The phase-space factor is elliptical in shape with an intercept on the energy axis at the energy where three-body decay becomes possible. As we can see in Fig. 1, the data at $E_d = 5$ MeV have backgrounds of this general shape. In particular, the steepest slope of the background occurs at the neutron threshold (indicated with an arrow

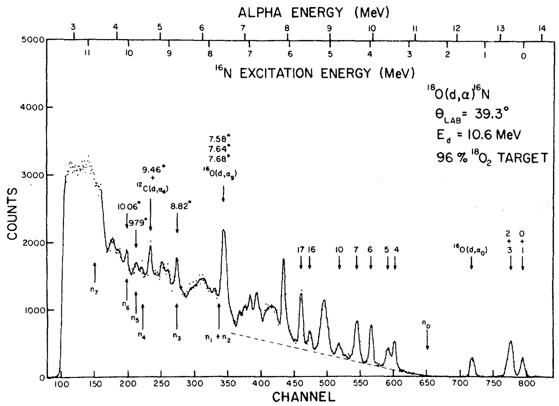

FIG. 2. Spectrum typical for $E_d \approx 10$ MeV. States of low excitation for which angular distributions were obtained are indicated with integer labels. The dashed line indicates the background used. Other selected groups are labeled with the ^{16}N excitation energy or the reaction produced by a target contaminant. Neutron thresholds are labeled n_i as indicated in Sec. III. C.

labeled "n"), which is what one would expect for an elliptical phase-space factor. However, if we look at Fig. 2 which is typical of the data at $E_d = 10-11$ MeV, we find that a linear background through the threshold seems to be a better approximation. Although the reason for the apparent linearity is not clear, we use the linear-background approximation for extracting cross sections. Since α groups corresponding to $E_x(^{16}\mathrm{N}) > 6$ MeV were generally not well resolved, cross sections were extracted only for groups of lower excitation energy. When the background deviated more than 5–10% from a straight line, a second straight line was used to approximate the background in that region of the spectrum, the results for both choices of background are given, with the second line setting a lower limit on the yield, and the difference between the two choices providing a measure of the uncertainty in the background.

With the background specified in this manner, the yields of individual groups were determined by the computer program PEAKFIT which was written by deForest.[23] The program fits a spectrum with a number of Gaussian peaks superimposed on a specified background using a previously described[24] nonlinear least-squares fitting procedure. In addition to providing the yield of each group, the program also gives an estimate of the uncertainty in the yield due to counting statistics and uncertainties in the fit for overlapping peaks. The only other source of substantial uncertainty in the yield is the uncertainty in the choice of background, which has been discussed.

D. Uncertanties

In addition to the uncertainties in the yields, uncertainties in the cross sections arise from all the other factors which enter into the calculation of the cross section. Except for a ±3.6% systematic error in the G (or solid angle) factor,[25] most other major uncertainties are believed to be random. The largest of these is the partial pressure of ^{18}O, and arises from the varying concentrations of impurity gases containing ^{16}O and ^{12}C. Comparison of the yields from $^{16}\mathrm{O}(d, \alpha_0)^{14}\mathrm{N}$ with the known cross sections[26] at 10.0 MeV provided a measure of the ^{16}O present. The results indicated ^{16}O concentrations varying between 2.5 and 4.5% during the course of a running period. Since the ^{12}C impurities are likely to be present in the form of CO_2, a reasonable estimate for the partial pressure due to impurities is $(3.8 \pm 1.5)\%$. Accordingly the cross sections were calculated assuming an ^{18}O purity of $(96.2 \pm 1.5)\%$.

A possible systematic error in angle associated with detector collimation misalignment was discovered after all of the data were taken. This misalignment results in an error of approximately $(0.6 \pm 0.3)^\circ$ in all the lab angles. Although the resulting error in the cross sections is less than 0.5%, the uncertainty in the center-of-mass angles is more substantial (−0.4 or +0.7°). Additional uncertainties include the integrated charge (up to 1.0% in some cases) and temperature of the target (0.3%). When added as random errors, these errors total 1.9% in addition to the errors in the yield and the G-factor error.

α energies were obtained by using the accurately determined excitation energies of Hewka, Holbrow, and Middleton[16] and a Q value of 4.244 MeV.[22] For α energies between 3.0 and 6.5 MeV, which is where all of the new levels occured at forward angles, the calibration of channel number versus α energy was determined by using the calculated energies of low-excitation ^{16}N groups at angles of 150 to 166°. By using constant amplifier gains for all angles, this calibration could then be used to determine α energies at forward angles to within ±15 keV. The contaminant groups from the $^{16}\mathrm{O}(d, \alpha)^{14}\mathrm{N}$ reaction to the 7.97- and 8.47-MeV levels of ^{14}N and the $^{12}\mathrm{C}(d, \alpha)^{10}\mathrm{B}$ reaction to the 3.59-MeV level of ^{10}B served as a check on the consistency of the method of calibration. These groups were all found to be within ±10 keV of their previously reported[1] excitation energies.

III. RESULTS

A. Levels Between 0.4- and 3.3-MeV Excitation Energy

In spite of the fact that the present experiment would be expected to be sensitive to the presence of two-particle, two-hole states such as those predicted by Eisenberg *et al.*,[10,11] no evidence is found for the existence of states between 0.4- and 3.3-MeV excitation energy. Admittedly this experiment hardly constitutes a systematic search for such levels. However, there is no indication of such levels over a fairly wide range of bombarding energies and scattering angles. In particular, there are three sets of data: (1) lab angles of 20 to 50°, incident energies of 4.75 to 5.3 MeV in 50-keV steps; (2) lab angle of 165.4°, incident energies of 5.75 to 8.75 MeV in 250-keV steps; and (3) angular distributions at incident energies of 10.0, 10.6, and 11.2 MeV. In all of these data there is no sign of any group with a yield of more than 10% of the smallest observed group, which is usually the first or third excited state. This negative result means that any state in this range of excitation energies must have a yield which is at least 25–40 times smaller than that of the average observed state with excitation energy less than 6 MeV.

B. Groups from the $^{18}O(d, n)^{19}F^*(\alpha)^{15}N$ Reaction

There were several broad α groups observed in the spectra which deserve special comment. These groups were observed in the spectra for $E_d \approx 5$ MeV and were originally believed to be ^{16}N groups at $E_x = 3.06$, 3.80, and 4.58 MeV. However, further study of these groups revealed that, although their energy varied like ^{16}N groups when the scattering angle was varied for a fixed deuteron energy, they occurred at essentially constant energy when the deuteron energy was varied for constant scattering angle. This behavior is illustrated in Fig. 1 which shows spectra at $E_d = 5.00$ and 5.15 MeV. In spite of the change of 150 keV in deuteron energy, the groups labeled "3.80" and "4.58" are at constant energy to within ±15 keV. The behavior of these groups indicates that they are the result of the two-step process, $^{18}O(d,n)^{19}F^*(\alpha)^{15}N$, where the $^{19}F^*$ decays by α emission to ^{15}N states.

Since a single ^{19}F level will produce a range of α energies corresponding to different ^{19}F recoil directions, the observed α-decay energies are only sufficient to specify a range of possible ^{19}F excitation energies. Assuming a range of α energies equal to twice the full width at half maximum of these groups, the ranges of ^{19}F excitation energies become 7.71 to 8.65, 8.72 to 9.48, and 9.59 to 9.93 MeV for the "4.58", "3.80", and "3.06" groups, respectively. The $^{18}O(p, \alpha)^{15}N$ results of Karadzhev, Man'ko, and Chukreev[27] indicate on the order of five ^{19}F levels within each of the latter two ranges.

The important point is that for the $^{18}O(d, \alpha n)^{15}N$ reaction there are α groups which correspond to strong final-state interactions between the ^{15}N and the α particle as well as α groups corresponding to strong final-state interactions of the ^{15}N and the neutron. The existence of such groups clearly implies that considerable caution should be exercised in identifying new levels. Only by checking the kinematic behavior of the α group with varying deuteron energy and scattering angle, can one identify which final-state interaction is effective. Therefore a tentative new level in ^{16}N has been definitely identified only if observed at more than one deuteron energy.

C. Energy Levels of ^{16}N

As the typical spectrum of Fig. 2 indicates, numerous levels of ^{16}N were observed via the $^{18}O(d, \alpha)^{16}N$ reaction. Energy levels were identified by the energy of the corresponding α group and its kinematic variation with deuteron energy and scattering angle. As previously mentioned, there were also α groups observed which came from the (d, α) reaction on ^{16}O and ^{12}C impurities in the target. These groups, along with a few ^6Li and ^7Li groups, often obscured possible ^{16}N groups over a fairly wide range of angles, thus making positive identification of some ^{16}N levels very difficult. On the other hand, some ^{16}N groups could be easily distinguished from these impurity groups, especially through use of comparable $^{16}O(d, \alpha)^{14}N$ spectra.[26]

A summary of all the levels of ^{16}N is provided by Fig. 3. The diagram at the left of Fig. 3 shows the levels observed in this experiment. All the levels below $E_x = 8.49$ MeV have also been seen in[16] the $^{14}N(t,p)^{16}N$ and in[6-8,15] the $^{15}N(n,n)^{15}N$ reactions and their energies have been taken from the results of Hewka, Holbrow, and Middleton,[16] except for the 8.06-MeV level which differs from the 8.04 MeV of Ref. 16. There are in addition a number of levels that have been seen in other experiments but not in this experiment. These levels are indicated on the diagram at the right which is labeled "unobserved levels." Of these levels the 1.29-, 1.73-, and 2.15-MeV levels are of doubtful existence. The levels at 4.725, 4.88, 4.98, 5.305, and 6.42 MeV are broad levels[7,15,16] which may be obscured by lack of resolution and uncertainties in background. The levels at 5.13 and 5.15 MeV have been reported[16] as a doublet, but are too closely spaced to be resolved in this experiment and are accordingly listed as one level at 5.14 MeV in the left-hand diagram. The level at 7.06 MeV has been observed[15] in $^{15}N(n,n)^{15}N$ but not in $^{14}N(t,p)^{16}N$ and is apparently[15] not the same level as the one listed at 7.01 MeV. The 9.9-MeV level is reported as the lowest $T = 2$ level[2,3] and is given a 0^+ spin-parity assignment. The 11.62-MeV level is the lowest observed

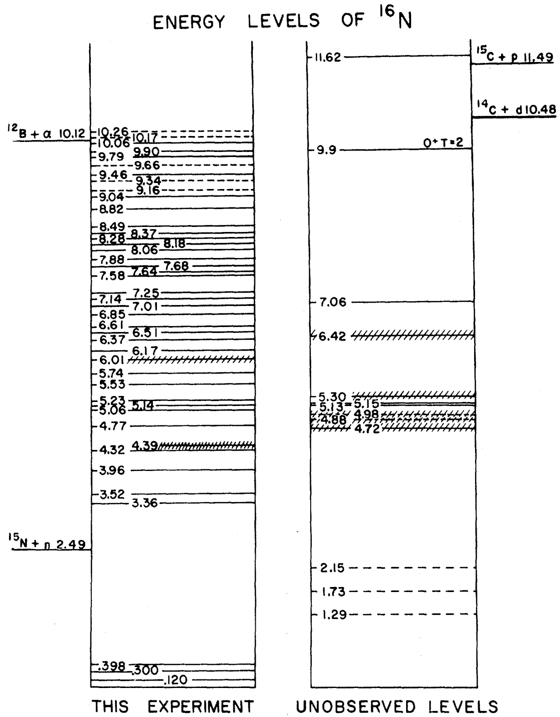

FIG. 3. Energy levels of ^{16}N observed in this experiment are indicated at the left. Previously observed levels not observed in this experiment are shown at the right.

level above the ones reported here and was seen as a ^{14}C$(d, n)^{15}$N resonance.[4]

The other levels above $E_x = 8.37$ MeV have not been previously reported, with the exception of the levels which McGrath[20] reports at 8.83 ± 0.05 and 9.47 ± 0.05 MeV from the ^{10}B$(^{7}$Li$, p)^{16}$N reaction. These two levels are confirmed by the present experiment. The definitely identified levels above $E_x = 8.37$ MeV are as follows: 8.49 ± 0.03, 8.819 ± 0.015, 9.035 ± 0.015, 9.459 ± 0.015, 9.794 ± 0.015, 9.90 ± 0.03, and 10.055 ± 0.015 MeV. In addition, there are tentatively identified levels indicated by dashed lines at 9.16 ± 0.03, 9.34 ± 0.03, 9.66 ± 0.04, 10.17 ± 0.03, and 10.26 ± 0.03 MeV. The tentatively identified levels are often obscured by other groups. They have been observed in at least a few spectra where they have been sufficiently separated from known contaminant groups to allow identification as a separate group. However, they are clearly observed at only a few angles or at only one deuteron energy, so that their identification as ^{16}N levels is not unambiguous.

As well as can be determined with the uncertainties in background, all these levels are fairly narrow, with their α groups having widths approximately equal to the experimental resolution of 70–100 keV. This means that the widths of the levels are probably less than half of this value, i.e., widths $\leq$40–50 keV. It is not surprising that the observed levels are all fairly narrow since, as we have mentioned, broad groups may be lost in the background. It is nevertheless somewhat striking that there are as many relatively narrow levels as the spectra indicate, since they are all (except for the ground-state quartet) unbound with respect to neutron emission by 1–10 MeV. This would indicate that these states have wave functions with very little overlap with the ^{15}N ground state plus a neutron.

The thresholds for neutron emission to excited states of ^{15}N are indicated on Fig. 2 with arrows labeled "n_i" where i refers to the ith excited state of ^{15}N. It can easily be seen that several groups lie very close to these thresholds. In particular, the states at 8.819, 9.794, and 10.055 MeV lie within ± 10 keV of the thresholds for neutron emission to the third, fifth, and sixth excited states of ^{15}N. The correlation between states of ^{16}N and thresholds for neutron emission to excited states of ^{15}N which is suggested by this result is discussed elsewhere.[28]

The level observed at 9.90 ± 0.03 MeV may be the same level as the one at 9.938 ± 0.007 MeV, which has been reported[3] as the lowest $T = 2$ level. If these two levels are the same level, then either the level is not $T = 2$ or there is a large violation of isospin conservation, since the yield for this group is of the same order of magnitude as neighboring groups.

D. Excitation Functions

An excitation function at a lab angle of 32.4° was taken for deuteron energies of 9.6 to 11.5 MeV in 100-keV steps. The purpose was to determine whether the energy dependence of the cross section for the low-lying levels was consistent with a direct-reaction mechanism. Figures 4(a)–(c) present the results for the groups leading to the following excited states: 4, 5, 6, 7 + 8 (unresolved), 16, and 17, where the numbering is the same as in Fig. 2. The cross sections have been calculated always assuming the largest possible background, since only this choice of background gives results consistent with widths of α_{16} and α_{17} as reported by Hewka, Holbrow, and Middleton.[16]

In looking at the data it is clear that several groups, especially α_4 and α_6, show some broad structure with half-widths of the order of 500 keV and peak-to-valley ratios of approximately 2 to 1. While the excitation functions with their fairly large energy steps would not be expected to be very sensitive to much narrower structure, it could be expected that substantial narrower structure would be reflected in a considerable scatter of points superimposed on this broad structure. The general lack of such scatter (only about six points show much deviation from the otherwise slowly varying structure) therefore suggests that there is relatively little sharp structure to the excitation curves. Several of the groups, especially α_5, are nearly constant over a major part of the range of the excitation function. The behavior of α_5 is very much like what one would expect for a direct reaction. The magnitude of the cross section is, however, lower than might be expected for a direct reaction, but could be accounted for if the angular distribution were peaked nearer 0° as would be expected from other experiments.[16,18,19] Thus the excitation functions are not particularly conclusive as to the presence of a direct-reaction mechanism, since for the most part they do not have a smooth energy dependence, while at the same time there is not much evidence for substantial resonant structure with widths less than a few hundred keV.

E. Angular Distributions

Angular distributions were taken at deuteron energies of 10.0, 10.6, and 11.2 MeV, and results were obtained for a number of low-lying groups which are indicated in Fig. 2. These groups are the only ones which do not suffer large uncertainties in yield because of difficulty in resolving the groups from other groups or because of large uncertainties in the background. The angular distributions for these groups are presented in Figs. 5(a)–5(i). The closed triangular points for the 10.0-MeV data were taken with a 12 500-Å foil, and because of the increased energy loss are actually 80 keV lower in bombarding energy. In spite of this energy shift, these points are usually in good agreement with other points at the same angles. This agreement tends to support the conclusion concerning the general lack of narrow resonance structure in the excitation functions. Except as otherwise shown, the error bars (excluding the G-factor error which affects the absolute but not the relative cross sections) are about the size of the points. In cases where the cross sections are sensitive to choice of background, the results are indicated as in Fig. 5(g), by a vertical bar with horizontal bars at the values corresponding to the two choices of background which were previously discussed. It should also be pointed out that the curves drawn through the points are only visual aids.

Figure 5(a) shows the results for α_0 plus α_1, because the two groups are generally not resolved. At the very forward and backward angles where it was possible to resolve the groups, the cross sections for the two groups have been indicated separately by open triangles and open circles as indicated by the labels on the 10.0-MeV points. These points should give an indication of their relative contributions to the summed cross sections. A similar situation occurs in Fig. 5(b) which presents the results for α_2 plus α_3. Figure 5(f) presents the results for α_7 and α_8, although there is generally only a very small α_8 contribution except at the two most forward angles. Figure 5(g) presents the results for α_9 and α_{10}. There is, however, no evidence of the broad α_9 group in the spectra, and the angular distributions should be essentially those of α_{10}. Qualitatively, it is clear that all of the groups up to α_7, except for α_5, show considerable similarity in the shape of their angular distributions from one deuteron energy to the next. This more or less energy independence of

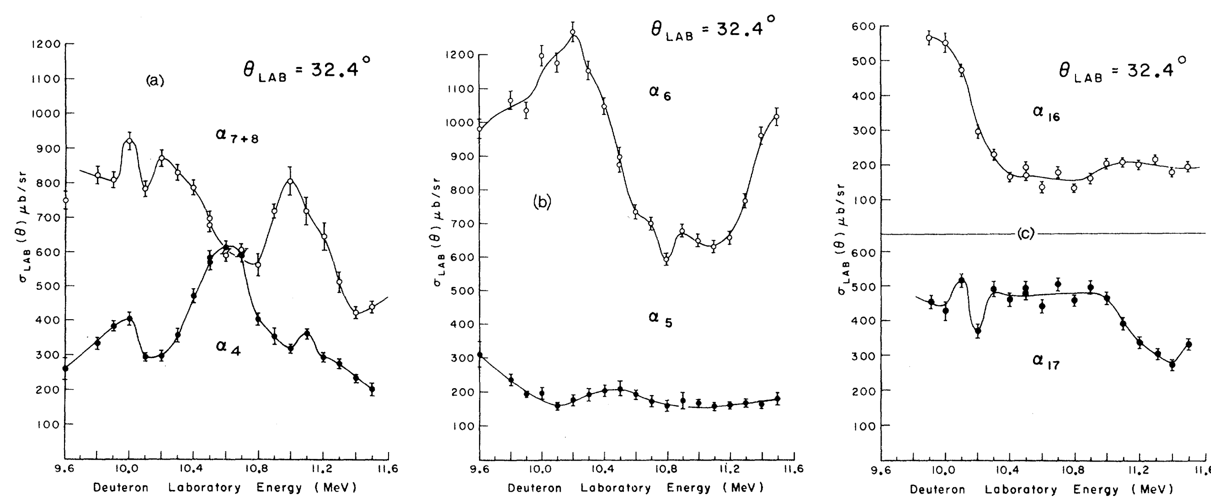

FIG. 4. (a)–(c) Excitation functions for selected groups as labeled at a lab angle of 32.4°. Solid curves are visual aids only.

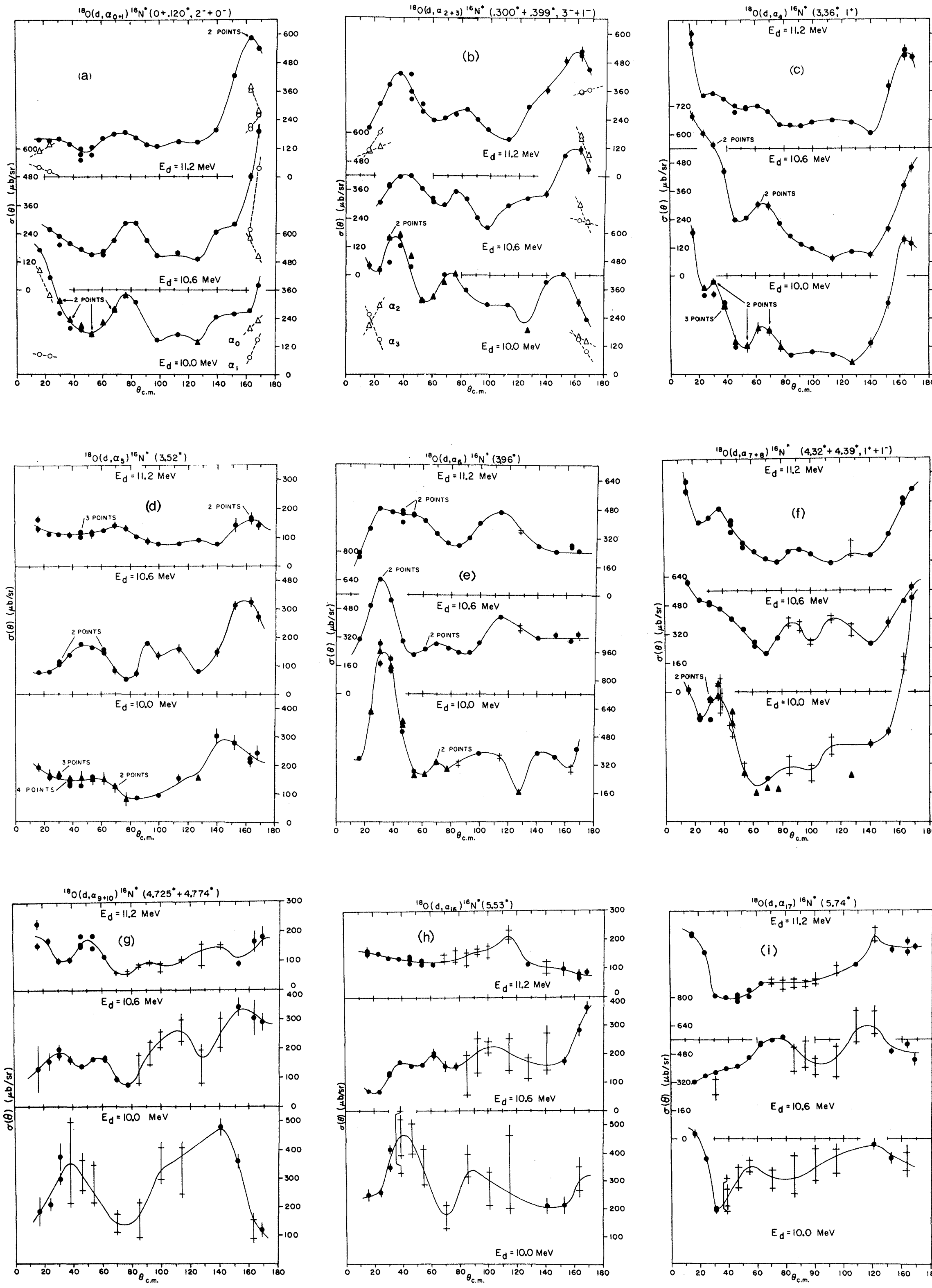

FIG. 5. (a)–(i) Angular distributions for selected groups as indicated. Excitation energies and spin-parity assignments, where available, are indicated at the top of each figure. See text for explanation of symbols.

shape is suggestive of a direct-reaction mechanism. In particular, α_4 and α_7, which are both identified as 1^+ states, are quite similar to each other in the qualitative features of the angular distributions. On the other hand α_5, α_{10}, α_{16}, and α_{17} all have angular distributions which vary considerably as a function of E_d, although these were the groups which showed the least energy dependence in the excitation functions taken at a lab angle of 32.4°.

F. Direct-Reaction Analysis

The discussion of the previous section gives some hope that the direct-reaction features may be strong enough to allow useful L-value information to be obtained. The two-nucleon transfer reaction is more complicated than the one-nucleon transfer reaction, because in general the total angular momentum $L(=l_1+l_2)$ of the two transferred nucleons will not be unique for a given final state.[29] Another complication is that the cross section is sensitive not only to the amplitudes of various shell-model configurations in the final nucleus (as in the one-nucleon case) but also to the phases of these amplitudes.[30,31]

The selection rules[29] for the present case reduce to $\pi=(-)^L$ and $J=L+S$ where the ^{16}N final nucleus has spin J, parity π, and where for a (d,α) reaction $S=1$. Thus, the natural parity states (1^-, 2^+, 3^-,...) limit L to one value ($=J$) while the unnatural parity states (0^-, 1^+, 2^-,...) permit two values of L, ($=J\pm1$). Furthermore, the population of a 0^+ state is forbidden, since $S=1$. In addition there is a selection rule such that states of even J cannot be formed if both nucleons are transferred from the same shell-model orbital. For the present case, this rule excludes primarily those configurations in 2^+ states which correspond to a $1p_{3/2}$ neutron and a $1p_{3/2}$ proton removed from the ^{18}O ground state.

In order to see whether the two-nucleon transfer is even qualitatively consistent with the experimental angular distributions, we will use the plane-wave Born approximation (PWBA).[32] Neglecting all the structure factors of the particles except for their spins and parities and considering only the kinematic factors, we write

$$\sigma(\theta)=\sum_L C_L |j_L(KR)|^2 .$$

We expect such a PWBA, even for a single L value, to give a reasonable fit only to the position and width of the first maximum. This is especially important for the unnatural parity states where two L values can contribute, because the first zero of $j_L^2(KR)$ occurs at essentially the same value of KR as the first maximum of $j_{L+2}^2(KR)$. The result is that for those angles where we expect a good fit for one value of L, we expect the contribution of the other value of L to be greatly underestimated. It would therefore be rather futile to attempt to extract reliable values for the relative contributions of the two L values using a plane-wave fit to the data. Accordingly, we shall be concerned only as to whether the positions of the primary peaks predicted by the plane-wave approximation agree with the data.

In the following discussion we shall assume that $R=5.0$ fm. This value is the approximate radius which is generally found to give good fits in this mass region [e.g., Hewka, Holbrow, and Middleton[16] use radii of 4.5 to 5.5 fm to fit their ^{14}N$(t,p)^{16}$N angular distributions]. Small changes of R may change the peak positions by a degree of two. However, it would require changes in R of greater than 1 fm to move the peak position of, e.g., $L=1$ or $L=3$ to the position of the $L=2$ peak for $R=5.0$ fm. Such a change would provide an anomalously large or small radius especially since, as we shall see, the choice of $R=5.0$ fm provides a reasonable account of the peak positions for states of known spin and parity. Thus if the experimental peak is within two or three degrees of that predicted, we can feel reasonably confident in the appropriate L value with the discrepancy being accounted for by a small change in R.

The angular distributions for $\alpha_0+\alpha_1$ [Fig. 5(a)] present considerable difficulty in interpretation as a pickup reaction because of the rapid change of the forward peak with changing deuteron energy. From the calculations of Elliott and Flowers[33] we expect that the 2^- ground state has a predominantly $(1p_{1/2})^{-1}(1d_{5/2})^1$ configuration, while the 0^- first excited state has a primarily $(1p_{1/2})^{-1}(2s_{1/2})^1$ configuration. Assuming the ^{18}O ground state is primarily two $1d_{5/2}$ neutrons outside the ^{16}O closed shell, we would expect that the ground state would be strongly populated while the first excited state would be weakly excited by a pickup mechanism. As best as can be determined by the lack of asymmetry in the $\alpha_0+\alpha_1$ peak in the spectra, this appears to be the case except at the very backward angles where a pickup description would not be expected to be successful. From the selection rules we would expect to have $L=1$ and $L=3$ components in the α_0 angular distributions with a small $L=1$ contribution from α_1. The forward angle rise in the 10.0-MeV data is consistent with an $L=1$ plane wave which peaks at an experimentally unobserved angle of approximately 10°. The very meager peaking of α_0 near 30° in the 11.2-MeV data is near the $L=3$ peak of 33°. The 10.6-MeV data represent a transitional shape between the two. We might, therefore, think of the data as a combination of

$L=1$ and $L=3$, with the $L=1$ component decreasing with increasing deuteron energy. From this viewpoint the decrease of the $L=1$ component indicates the inadequacy of the plane-wave approximation, since we would expect the relative amounts of $L=1$ and $L=3$ to be determined primarily by the structure factors which are energy independent. Similar behavior is apparent for some of the other groups.

The 3^- second excited state and the 1^- third excited state are the other two states formed from the $(1p_{1/2})^{-1}(1d_{5/2})^1$, and $(1p_{1/2})^{-1}(2s_{1/2})^1$ configurations. We would therefore expect a strong $L=3$ contribution from α_2 and a weak $L=1$ contribution from α_3. While α_3 appears to be generally much smaller than α_2 in the 10.0- and 10.6-MeV data except at the extreme angles, α_3 is actually somewhat larger than α_2 for most angles of the 11.2-MeV data. In spite of this change in the relative magnitudes of α_2 and α_3, the angular distributions all have a primary forward peak near 38° as compared to a peak positon of 35° for $L=3$. The nature of this agreement is shown in Fig. 6(a), which shows the 10.6-MeV data and the arbitrarily normalized calculated curve for $R=5.0$ fm. The data would be more accurately reproduced by a radius of 4.5 fm.

The fourth and seventh excited states [Figs. 5(c) and 5(f)] are 1^+ states and should therefore have $L=0$ and $L=2$ contributions. Both sets of data show a rise at the most forward angles which could be an $L=0$ component, since it should peak at 0°. In addition, the α_4 data show a secondary maximum at about 30° and the α_7 data show a similar maximum near 37°. These values compare favorably with the expected $L=2$ peak positon of approximately 31° for α_4 and 35° and α_7. However, if we interpret the forward structure of these angular distributions as a combination of $L=0$ and $L=2$, the energy-dependent change in the shape of the curves near 30° forces us to assume either that the relative magnitudes of the $L=0$ and $L=2$ components are changing with energy, or that the magnitude of the $L=0$ minimum (which should occur near 25°) is changing sufficiently to make the apparent height of the $L=2$ peak change substantially. Neither alternative is very attractive in terms of the picture of a simple direct reaction which would predict the structure to be nearly energy-independent.

In summary, the ^{16}N groups of known spin and parity which appear to proceed partially by a direct-reaction mechanism have angular distributions which show peaks at angles which are consistent with the PWBA. There are, however, energy-dependent effects evident, especially in those cases where two L values are allowed. It is likely that this behavior is due to a combination of distortion effects and compound-nucleus effects. Similar behavior has been commented on by Newns[32] in two cases of (^{3}He,p) reactions. In both cases both $L=0$ and $L=2$ contributions are allowed by the selection rules, although structure calculations indicate $L=0$ should be dominant in one case and $L=2$ in the other. Each case shows an energy-dependent behavior in which the proper L value dominates at higher energies and the other L value appears to dominate at lower energies. Similar competition between $L=0$ and $L=2$ components is evident in the ^{16}O$(d, \alpha)^{14}$N data of Yanabu *et al.*[34] In all of these cases the rather large variations are observed over a wider energy range (of the order of 5 MeV) than is the case in the present reaction. Nevertheless, while the plane-wave approximation is not sufficient to completely describe the reaction, it may allow identification of the participating L values.

Assuming that the major forward peaks of the angular distributions are due to a direct-reaction mechanism which is at least a major influence on the shape of the angular distributions, then we can attempt to extract tentative L values using a plane-wave interpretation. Of particular interest in this regard is the sixth excited state. As shown in Fig. 5(e) the 10.0- and 10.6-MeV angular distributions for α_6 exhibit a strong peak at about 32°, which corresponds to $L=2$. The nature of the agreement is illustrated in Fig. 6(b) which shows the 10.6-MeV data and the corresponding curve for $j_L^2(KR)$ with $R=5.0$ fm. The much broader peak in the 11.2-MeV data would appear to be due to a superposition of the $L=2$ peak with another peak at about 53°. This second peak could be either $L=4$ or a compound-nucleus effect. In either case the angular distributions seem to be fairly well character-

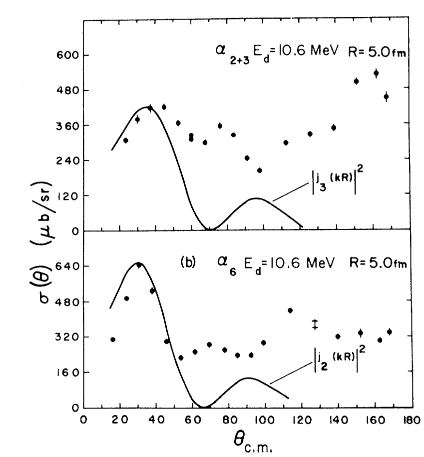

FIG. 6. Comparison of typical plane-wave calculations with experiment. Calculated curves are arbitrarily normalized.

ized as $L=2$. This L value would imply a spin of 1, 2, or 3, and positive parity, in agreement with the $^{14}N(t,p)^{16}N$ results of Hewka, Holbrow, and Middleton[16] as opposed to the negative-parity results of Refs. 6 and 18. However, the results of the $^{15}N(n,n)^{15}N$ total-cross-section measurements[6] actually only restrict the spin as being $J \geq 1$, because the group is not completely resolved and the negative parity is based on a marginally significant minimum before the peak which is interpreted as s-wave interference. Thus, on the basis of the neutron data, the most strongly indicated assignment is 1^-, but the results are not completely inconsistent with a $(1,2,3)^+$ assignment. In addition, the $L=1$ plane-wave fit to the 4-MeV $^{14}C(^3He,p)^{16}N$ data[18] does not appear to be much preferable to an $L=2$ fit. Indeed, the same authors have recently[19] found $L=2$ to be preferable at higher incident energies. Considering all the experimental results, it appears that the most probable assignment is $(1,2,3)^+$. The 1^+ assignment is least likely, since neither the present results nor the $^{14}N(t,p)^{16}N$ results[16] show any sign of an $L=0$ component which would also be expected. We might expect that the structure factors could reduce the $L=0$ contribution to insignificance in one reaction or the other, but it would seem improbable to have this occur for both reactions. The choice between a 2^+ and a 3^+ assignment depends on the interpretation of the broadening of the primary peak in the present data for $E_d=11.2$ MeV. If we interpret the extra width as being due to an $L=4$ component, then the assignment must be 3^+. This interpretation would be consistent with the previously described energy-dependent effects where two L values are possible. The 3^+ assignment would agree nicely with the calculations of Wong,[35] which predict the lowest 3^+ state to be close to the lowest 1^+ state. If the extra width is not due to an $L=4$ component, the 2^+ assignment becomes most probable, although the 3^+ assignment is still not ruled out. A 2^+ assignment would be more nearly consistent with the $J \geq 1$ result of Fossan *et al.*,[6] i.e., the effect of the resolution which is necessary to produce the observed results is less for $J=2$ than for $J=3$. Lacking more definite information on the presence of an $L=4$ component in the angular distributions, the 2^+ and 3^+ assignments for the 3.96-MeV level appear equally probable and preferable to a 1^+ assignment.

As we have noted before, the fifth excited state shows no sign of a significant direct-reaction component in its angular distributions. Since the neighboring groups appear to be partially populated via a direct reaction, the lack of direct features should be indicative of the nature of the 3.52-MeV level. One possibility is that the level is 0^+, which would be forbidden by the selection rules for a pickup reaction. This would agree with the tentative 0^+ of Fossan *et al.*[6] However, as with the 3.96-MeV level, their assignment is only a lower limit because of experimental resolution. In addition a 0^+ level would also be forbidden by selection rules for the $^{14}N(t,p)^{16}N$ and $^{14}C(^3He,p)^{16}N$ reactions,[16-19] which contradicts the observed $L=1$[16,18] or $L=2$[19] stripping patterns. It is therefore probable that the $(0,1,2)^-$ or the $(1,2,3)^+$ assignment is correct and that the absence of a corresponding $L=1$ or $L=2$ peak in the α_5 angular distributions is due to a small structure factor for the $^{18}O(d,\alpha)^{16}N$ reaction. A small structure factor could result either from a small ^{18}O parentage for the state or from a highly destructive coherence of the various configurations in the wave function.

One would have considerably more confidence in the L values if they were confirmed by reasonable distorted-wave Born-approximation (DWBA) fits or by angular distributions which were more unambiguously direct. One might especially hope that the energy dependence of the relative magnitudes of allowed L values would be partially accounted for by a DWBA calculation.

IV. CONCLUSIONS

This experiment has provided information about ^{16}N levels in two regions of excitation energy, that below 6 MeV and that between 8.4 and 10.3 MeV. In the first region no evidence was found for the existence of levels with excitation energies between 0.4 and 3.3 MeV. The fourth, sixth, and seventh excited states appear to be populated sufficiently by a direct-reaction mechanism to extract tentative L values. The results for the fourth ($E_x=3.36$ MeV) and seventh ($E_x=4.32$ MeV) excited states are consistent with previous 1^+ assignments. The sixth ($E_x=3.96$ MeV) excited state is characterized by $L=2$ and has most probably a 2^+ or 3^+ assignment. The absence of a pickup mechanism in the fifth ($E_x=3.52$ MeV) excited state suggests a small spectroscopic factor.

In the second region of excitation energy, levels were identified at 8.49 ± 0.03, 8.819 ± 0.015, 9.035 ± 0.015, 9.459 ± 0.015, 9.794 ± 0.015, 9.90 ± 0.03, and 10.055 ± 0.015 MeV. Additional levels were tentatively identified at 9.16 ± 0.03, 9.34 ± 0.03, 9.66 ± 0.04, 10.17 ± 0.03, and 10.26 ± 0.03 MeV. The levels at 8.82, 9.79, and 10.06 MeV appear to be correlated with thresholds for neutron emission to excited states of ^{15}N.

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