$C^{13}(d,n)N^{14}$ and $O^{18}(d,n)F^{19}$ Differential Cross Sections at 3.9-MeV Bombarding Energy*

R. E. BENENSON† AND B. YARAMIS‡
Columbia University, New York, New York

(Received 16 August 1962)

The $C^{13}(d,n)N^{14}$ reaction has been restudied with the purpose of obtaining absolute differential cross sections. The intention has been to extract stripping reduced widths for the four lowest energy levels in N^{14} and to investigate an anomalous angular distribution from previous work on this reaction. A table of θ^2, the reduced widths for stripping, is given along with a brief discussion of the consistency of the N^{14} shell-model assignments with the stripping analysis. The second experiment reported in this paper on the $O^{18}(d,n)F^{19}$ reaction was based on the suggestion that neutrons which leave F^{19} in its 2.78-MeV level might be undergoing spin-flip stripping. A more strongly forward angular distribution than an $L_p=2$ distribution was found; this L_p value had been suggested if the 2.78-MeV level had a 7/2+ assignment and spin-flip stripping is an important mechanism. Since the experiment was completed, evidence has appeared which favors a low spin value for the 2.78-MeV level and invalidates the reaction as an indicator of the spin-flip mechanism.

I. INTRODUCTION

THE extraction of reduced widths from stripping reactions[1] has afforded an opportunity for closer study of nuclear bound-state configurations. The level configurations of N^{14} have been of particular interest ever since the early attempts to explain the unexpectedly long lifetime of the C^{14} beta decay; a careful study of N^{14} configurations and summary of previous work has been given by Warburton and Pinkston.[2]

The first part of this paper deals with a restudy of the angular distribution of neutrons from the $C^{13}(d,n)N^{14}$ reaction. This study is oriented to the measurement of absolute differential cross sections in order to extract reduced widths. To facilitate measurement of absolute cross sections a gas target and fast neutron spectrometer of reasonably well known efficiency for detection of neutron recoils were employed.

A second purpose served in obtaining differential cross sections for the $C^{13}(d,n)N^{14}$ reaction is to resolve an apparent disagreement in two independent measurements on this reaction of the angular distribution of neutrons which leave N^{14} in its ground state. The measurement which established the N^{14} ground-state parity used an ion chamber to detect neutrons emerging from a very thick target.[3] Only the highest pulses from the neutron induced recoils were counted. The second measurement employing nuclear emulsions[4] and a thin target obtained an angular distribution more strongly peaked in the forward direction than consistent with the required $L_p=1$ proton capture. Although the statistics were poor in the emulsion measurement, the possibility remained open that the thin-target data happened to give rise to an anomalous angular distribution at the reasonably well defined bombarding energy. In distinction, the thick-target data could be considered to have averaged many bombarding energies to yield the correct result. The bombarding energy of the present experiment was chosen to approximate the thin-target measurement in order to search for an anomalous angular distribution.

The second experiment described in this paper was based on the suggestion that another example of spin-flip stripping might be obtained from the $O^{18}(d,n)F^{19}$ reaction.[5,6] Spin-flip stripping was postulated by Wilkinson[7] to explain how the capture of a $L_p=1$ neutron could be consistent with the transition from a 3+ state to a $\frac{1}{2}-$ state in the $B^{10}(d,p)B^{11}$ reaction. Some experimental evidence exists[8] which attributes a spin of $\frac{7}{2}$ or $\frac{9}{2}$ to the 2.78-MeV level of F^{19}. If the spin were $\frac{7}{2}$ and the parity positive this level could be excited by capture of a proton with $L_p=4$ in ordinary deuteron stripping on O^{18}, but $L_p=2$ capture would signify spin-flip stripping.

Either an assignment of $\frac{7}{2}+$ to the F^{19} 2.78-MeV level followed by an observed $L=2$ distribution, or further polarization data are needed if the $O^{18}(d,n)F^{19}$ reaction is to detect the spin-flip mechanism. In any case, a determination of the 2.78-MeV level spin and parity appears to be most useful to the understanding of F^{19} level systematics. Theoretical analyses[9,10] tend to favor a $\frac{9}{2}+$ assignment; on the other hand, some recent work by a Russian group[11] indicates that the spin of the level is actually $\frac{1}{2}+$ or $\frac{3}{2}+$. The results of the present experiment are consistent with a low spin for the 2.78-

* Work partially supported by U. S. Atomic Energy Commission.
† Permanent address: City College of New York, New York.
‡ On leave from the University of Istanbul, Istanbul, Turkey, as an International Atomic Energy Agency Fellow.
[1] M. H. Macfarlane and J. B. French, Rev. Mod. Phys. **32**, 567 (1960).
[2] E. K. Warburton and W. T. Pinkston, Phys. Rev. **118**, 733 (1960).
[3] D. A. Bromley and L. M. Goldman, Phys. Rev. **86**, 790 (1952).
[4] R. E. Benenson, Phys. Rev. **90**, 420 (1953).
[5] H. T. Richards (private communication, 1957).
[6] J. E. Bowcock, Phys. Rev. **112**, 923 (1958).
[7] D. H. Wilkinson, Phys. Rev. **105**, 666 (1957).
[8] F. Ajzenberg-Selove and T. Lauristen, Nucl. Phys. **11**, 1 (1959).
[9] J. P. Elliott and B. H. Flowers, Proc. Roy. Soc. (London) **229**, 536 (1955).
[10] G. Rakavy, Nucl. Phys. **4**, 375 (1957).
[11] S. S. Vasil'ev, E. A. Romanovsku, and G. F. Timushev, Soviet Phys.—JETP **14**, 741 (1962).

MeV level; unfortunately the data at forward angles are not sufficiently good to permit an unambiguous assignment of an L_p value.

Other than substitution of O^{18}-enriched gas for the C^{13}-enriched gas in the target chamber, the experimental conditions were identical for the two reactions described in this paper.

II. EXPERIMENTAL METHOD

For both experiments neutron groups were observed by a gas-recoil fast-neutron spectrometer[12] filled with research grade propane[13] for most of both experiments to an absolute pressure of 31.8 psi. The axis of the spectrometer was oriented at angles ranging from 0° to 120° with the beam direction. The enriched target gases at approximately $\frac{1}{3}$ atmosphere pressure were confined by means of a nominally 1/40-mil nickel foil to a gas target chamber $1\frac{1}{8}$ in. long. The energy loss in the target was estimated to be approximately 240 keV for the $C^{13}(d,n)N^{14}$ experiment and 200 keV for the $O^{18}(d,n)$ runs. The machine energy was set by means of a generating voltmeter which at the time of the experiments was the only instrument available for machine energy measurement. The generating voltmeter was calibrated at the $Li^7(p,n)Be^7$ threshold using the atomic beam; attempts to calibrate with the HH^+ beam at 3.76 MeV were unsuccessful because of deuterium contamination. Greater effort at energy calibration was not expended because of the thickness of the target relative to the machine energy uncertainty. For the $C^{13}(d,n)N^{14}$ runs the energy of the beam at target center is considered to be $\bar{E}_d=3.89\pm0.05$ MeV; for the $O^{18}(d,n)F^{19}$ runs it is considered to be $\bar{E}_d=3.96\pm0.05$ MeV. The choice of $\bar{E}_d=3.89$ MeV for the $C^{13}(d,n)N^{14}$ study came about for historical reasons as described in the Introduction.

For the $C^{13}(d,n)N^{14}$ reaction two independent angular distributions were measured at a spectrometer filling pressure of 31.8 psi absolute. At this pressure, the neutron groups corresponding to N^{14} left in its ground, 2.31-, and 3.95-MeV levels give rise to easily identified peaks in the pulse-height distribution.

The system of collimation of proton recoils in the spectrometer required that a lower filling pressure be employed to identify the peak corresponding to N^{14} left in its 4.91-MeV level. The propane filling pressure was lowered to 21.7 psi absolute after which measurements were made only at laboratory system angles of 0°, 20°, and 30°. Although the 4.91-MeV level pulse heights could not be resolved from those arising from neutrons left in the N^{14} 5.10-MeV level, the 4.91-MeV level gives rise to an $L_p=0$ angular distribution highest at 0° while the 5.10-MeV level does not.[4] The assumption was made that a 0° measurement would permit the 4.91-MeV level reduced width to be ascertained to a good approximation by fitting the experimental differential cross section at that angle to a tabulated $L_p=0$ theoretical differential cross section. At angles greater than 0° the 5.10-MeV level neutrons are responsible for larger and larger fractions of the composite peak. The 20° and 30° data were taken in the hope of resolving the composite groups by reference to the emulsion data,[4] and served as a check on the deduction of spectrometer efficiency for detection of the 3.95-MeV level neutrons under two different operating conditions.

Gas targets afford great convenience in determining the number of target atoms/cm^2, but generally give rise to larger background than do solid targets. The background appears after a protracted run to come from both foil and beam stop. Energy loss in the gas would affect background neutron energies from the beam stop only. Backgrounds for the $C^{13}(d,n)N^{14}$ were taken both with hydrogen gas of negligible stopping power and with neutral CO_2 of the same stopping power as the $C^{13}O_2$-enriched target gas. Backgrounds for the principal $O^{18}(d,n)F^{19}$ run were with normal oxygen in the target chamber. For most of the background spectra the change of stopping power made little difference; near the sharply descending low-energy background spectra, however, an increase in stopping power shifted the spectrum pulse heights downward.

The target gas for the $C^{13}(d,n)N^{14}$ run was carbon dioxide[14] containing 53.1 at.% of C^{13}. The lower stopping power of hydrocarbon gases would make their use desirable, but unlike hydrocarbon gases carbon dioxide remains stable under bombardment. After manufacture from elemental carbon its chemical composition is well known. Unfortunately, only one atom out of every six was useful for the reaction; in order to maintain reasonable counting rates, the target pressure used resulted in larger energy spreads of both deuterons and neutrons than desirable.

Since absolute cross sections were not of primary interest in the $O^{18}(d,n)F^{19}$ runs, an attempt was made to produce solid targets by oxidizing tantalum sheets in the vapor pressure at room temperature of D_2O^{18}. These targets proved unstable under bombardment, so that oxygen enriched in O^{18} to 65 at.%[14] was used in gaseous form. A thin layer of gold was evaporated onto the first of the 1/40-mil nickel foils used to contain the gas in order to protect them from oxidation and failure. Later experience at the standard 1-μA beam current indicated that the gold was unnecessary.

At various intervals deuterium was inserted into the target chamber, and both energy and spectrometer efficiency calibrations were performed using the $D(d,n)He^3$ reaction.

Two complete angular distributions were measured for the $O^{18}(d,n)F^{19}$ reaction at separated intervals, and these runs were followed by an investigation of spectra at forward angles.

[12] R. E. Benenson and M. B. Shurman, Rev. Sci. Instr. **29**, 1 (1958).
[13] Obtained from Matheson Company.
[14] Obtained from Isomet Corporation.

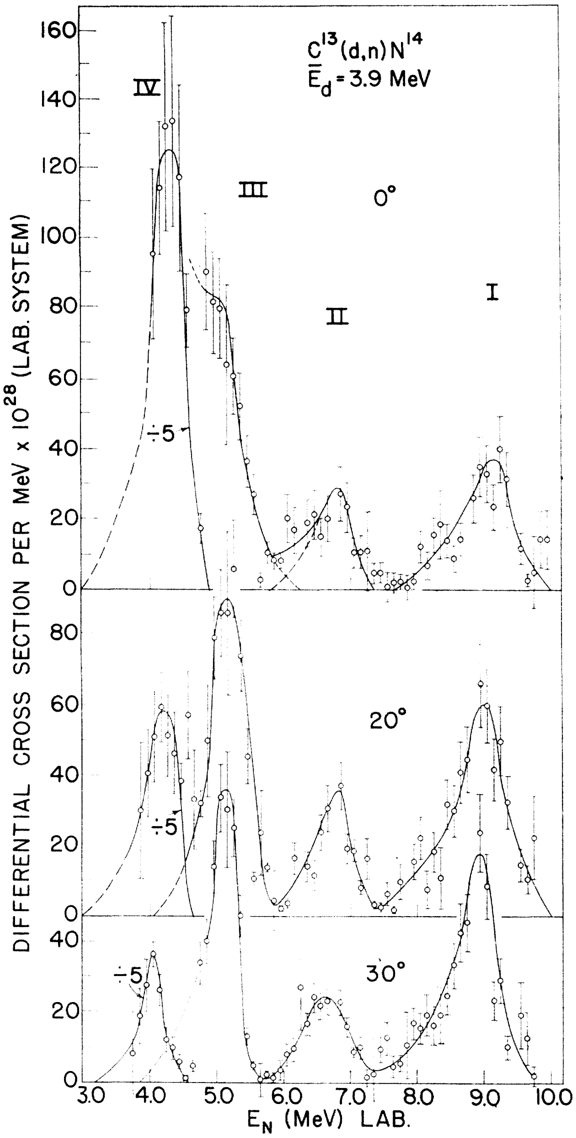

FIG. 1. Representative pulse-height spectra for the $C^{13}(d,n)N^{14}$ reaction at laboratory system angles of observation 0°, 20°, and 30°. Peaks I, II, III, and IV correspond, respectively, to N^{14} left in its ground, 2.31-, 3.95-, and 4.91-MeV levels. Peak IV also contains a contribution from the 5.10-MeV level. The spectra have been corrected for the variation of spectrometer efficiency with neutron energy. Each spectrum is a superposition of three runs.

For the first of two runs the angles of observation in the laboratory system were 0°, 10°, 20°, 30°, 45°, 60°, 90°, and 120°; for the second of the two runs the 10° angle was omitted. The first angular distribution was made with the spectrometer operating with less than optimum resolving power owing to contamination of the propane from outgassing of the spectrometer walls. At angles of observation above 30° the data of the second run yielded a well-resolved peak corresponding to F^{19} left in its 2.78-MeV level; at smaller angles difficulty was encountered in resolving this peak from a sharply descending spectrum of pulses. Backgrounds were large, and correction had to be made for some electronic circuit drifts between the time of taking data with O^{18} in the target chamber and the time of measuring background. To alleviate the difficulties of count assignment some further data were available at 20° and 30° from an incomplete run, and, finally, the measurements at 0° and 20° were repeated at a later date. On the basis of all data the 0° and 20° differential cross-section uncertainty could be reduced to limits considered just tolerable.

At each angle of each run a check was made for loss of counts from a peak due to accidental anticoincidence in the spectrometer, and from this check a correction factor could be calculated.[15] Pulses from a 60 pulse per second mercury switch pulser were fed into the grid of the first preamplifier tube of the spectrometer central volume. These pulses were handled by the electronic equipment exactly as if they were true counter pulses, and were adjusted so that after amplification they fell in channels of the multichannel analyzer above the highest energy pulses of the neutron spectrum. The number of these pulses appearing in the analyzer in one minute was recorded. During this minute the beam current was held as closely as possible to that of the actual run, and the ratio of this number to 3600 gave the correction factor. The uncertainties inherent in this procedure are discussed in the Appendix. The pulser signals also permitted monitoring electronic circuit drifts.

III. EXPERIMENTAL RESULTS

Three $C^{13}(d,n)N^{14}$ reaction pulse-height distributions are shown in Fig. 1 for laboratory system angles 0°, 20°, and 30°. Only these three angles include identifiable peaks for neutrons which leave N^{14} in its 4.91-MeV level (group-IV peak) as well as the ground state, 2.31-, and 3.95-MeV level peaks, groups I, II, and III, respectively. As mentioned in Sec. II the group-IV peak also includes counts from neutrons which left N^{14} in its 5.10-MeV level. The three spectra are each weighted averages of the three runs; the entry in each 100-keV interval is a weighted average of as many runs as contribute to that interval. Each run does not contribute to each interval: The two at 31.8-psi filling pressure were recorded in intervals slightly greater than 100 keV; the data taken at 21.7-psi filling pressure do not contribute effectively to either groups I or II due to the very low counting efficiency for these neutrons. The occasional outsize error bars occur when only one run with poor counting statistics contributed to a 100-keV interval.

Prior to averaging, the number of counts per three pulse-height analyzer channels were multiplied by appropriate factors in order to convert counts to differential cross section per MeV. The factors comprised

[15] Thanks are due to W. Haeberli for suggesting the use of artificial pulses as gain checks and for valuable discussions concerning the accidental anticoincidence correction.

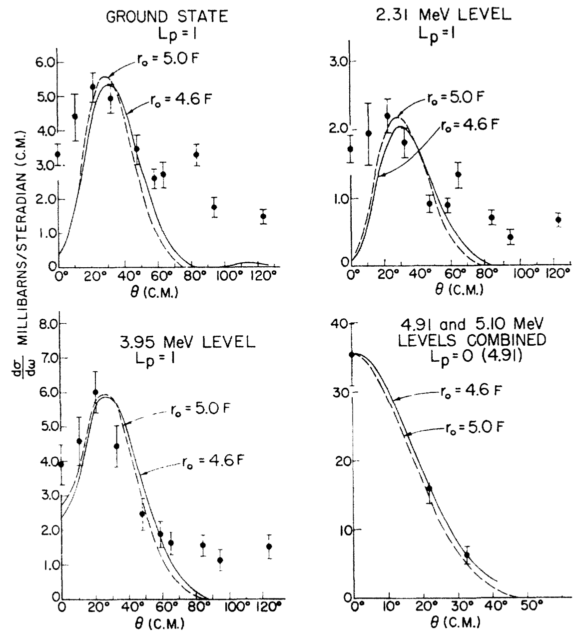

FIG. 2. Experimental and theoretical differential cross sections in the center-of-mass system for neutrons which leave N^{14} in its lowest four energy levels from the $C^{13}(d,n)N^{14}$ reaction. The error bars represent combined uncertainties in relative cross sections. The uncertainty in ordinate scales is estimated to be $\pm 12\%$.

terms from formula (2) of reference 12 and the ratio of the number of analyzer channels per MeV of neutron energy. The factor $[1-\cos 2\phi_0]$ in the formula, the term proportional to the solid angle of acceptance of recoils, depends sensitively on neutron energy. Since all Q values of the reaction are well known,[8] these neutron energies were calculated from reaction kinematics. A pulse height vs neutron energy calibration curve for each run was obtained from all the observed peaks, and further points for the curve were supplied from the calibrations using the $D(d,n)He^3$ reaction In each pulse-height spectrum the counts per energy interval associated with an identifiable peak were all multiplied by the same conversion factor; in other words, this conversion factor changes discontinuously from peak to peak. A peak shape of the raw data is preserved. A somewhat arbitrary break had to be made in some cases where no clear-cut valley was in evidence.

The weighting per interval was according to internal errors. These errors were evaluated for each energy interval of each run first by combining the statistical and accidental anticoincidence uncertainties for both target plus background and background measurements as described in the Appendix. Another combination was then made of the uncertainties in machine energy, target pressure, spectrometer filling pressure, neutron energy dependence on spectrometer angle setting, limit of validity of the count conversion formula, and effect of electronic circuit drifts on background subtraction. This second combination yielded an uncertainty varying slightly from point to point, roughly an 8 to 10% error, which was then combined with the statistical and accidental anticoincidence uncertainties to get an over-all error per spectrum point. A weighted mean cross section per energy interval and its error could then be calculated in the usual manner and were plotted on Fig. 1.

The spectra at the remaining angles of observation, 10°, 45°, 55°, 60°, 80°, 90°, and 120° in the laboratory system are similar to those shown in Fig. 1 for groups I, II, and III. The 4.91-MeV peak did not appear, and the problem of assigning counts to the group III peak was generally intermediate in difficulty between the 0° and 20° group III peaks.

In obtaining differential cross sections from the pulse-height spectra further uncertainties in addition to the combined uncertainty discussed above appeared as a result of ambiguity in assigning counts to a given peak. Two such uncertainties were considered: shape and normalization. Shape errors were included in almost all cases, but were important only when there was no valley to the left of a given peak. In these cases a fit had to be made to a plateau using monoenergetic neutron spectra shapes approximately normalized. Some error arose in choice of a spectrum shape. The normalization uncertainty was calculated from the same uncertainties as discussed for Fig. 1 points but now combining uncertainties of just three points at the shoulder of the plateau representing an unresolved peak.

The angular distributions obtained for the ground state, 2.31, 3.95, and combination of the 4.91- and 5.10-MeV levels are shown in Fig. 2. The error bars represent the combined uncertainties mentioned above and are considered as uncertainties in relative differential cross sections. The uncertainty in the absolute ordinate scales is considered to be $\pm 12\%$ based on the uncertainty in (1) calibrations using $D(d,n)He^3$ reaction, and (2) the sources of error encountered in using the spectrometer as an absolute instrument at energy where calibrations were not made. These latter uncertainties are discussed in the Appendix.

Superimposed on the experimental points of Fig. 2 are the theoretical angular distributions taken from Lubitz's tables[16] and calculated for two "reasonable" radii: 4.6 and 5.0 F. A "best" fit was made by eye. In addition, using the technique described in the back of the tables, the radius which made theoretical and experi-

TABLE I. Values of θ^2 deduced from stripping peaks.

	$r_0=4.6$ F	$r_0=5.0$ F	"best fit r_0"
Ground state	0.029	0.028	0.022
2.31-MeV level	0.023	0.025	0.023
3.95-MeV level	0.017	0.017	0.016
4.91-MeV level	<0.050	<0.049	<0.054

[16] C. R. Lubitz, University of Michigan Report, 1957 (unpublished).

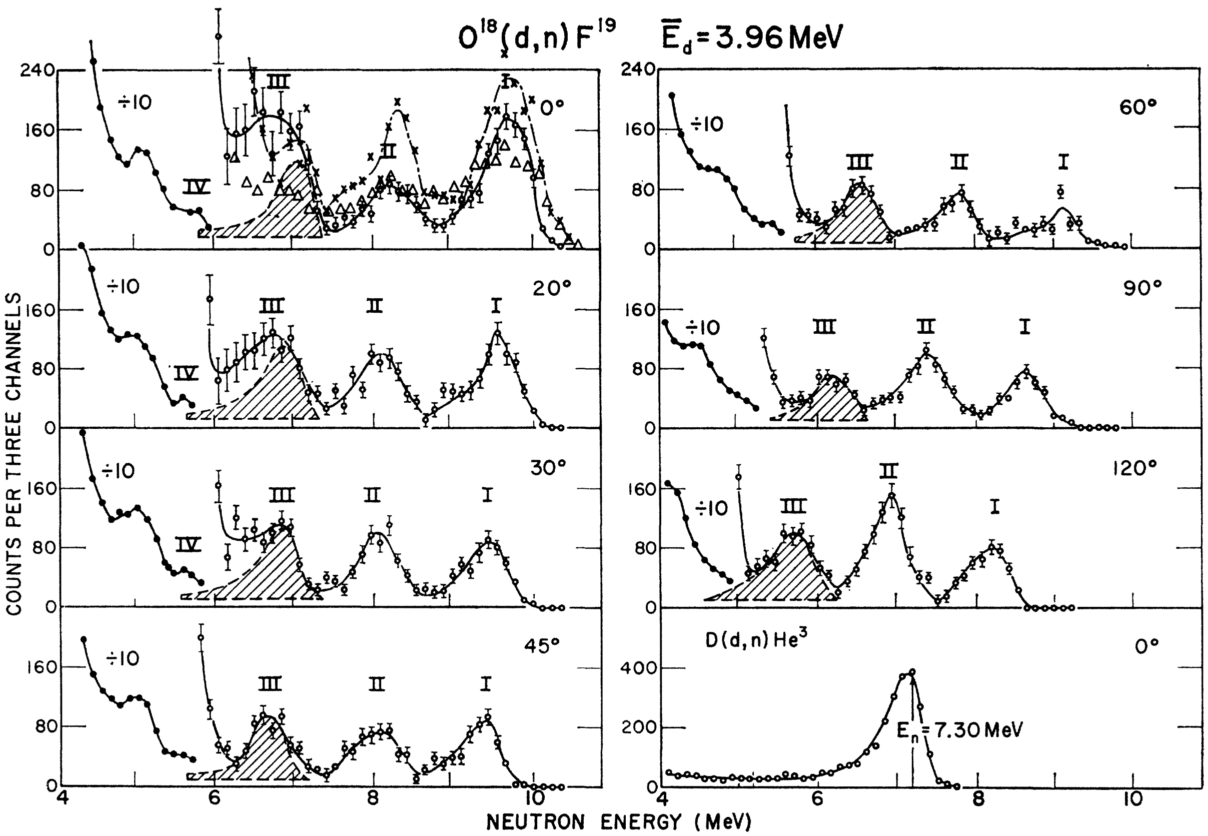

FIG. 3. Spectra of the second run of the $O^{18}(d,n)F^{19}$ reaction. The peaks marked III correspond to F^{19} left in its 2.78-MeV level. The dashed horizontal lines under these peaks represent the estimated low-energy tails of the peaks I and II. The dashed monoenergetic spectrum shown under peak III at 0° has been drawn after consideration of auxiliary data and of the effect of electronic drifts while taking backgrounds as discussed in the text. The spectra are uncorrected for the rapid decrease of spectrometer efficiency with increasing E_n. Error bars are from counting statistics only. The points marked "X" and the triangles on the 0° plot represent data from supplementary runs.

mental peaks coincide was calculated for each of the three $L_p=1$ distributions. These latter radii were, respectively, 5.55, 5.78, and 5.72 F for the ground, 2.31,- and 3.95-MeV level distributions; radii larger than usual for a nucleus of this mass number. The quantity θ^2, the stripping reduced width of reference 1, was extracted from the highest points of the experimental distributions, and values of θ^2 are shown in Table I for the various radii.

The $O^{18}(d,n)F^{19}$ data are represented by the pulse-height spectra of the second run shown in Fig. 3. The data have not been corrected for the variation of spectrometer efficiency with neutron energy. The group labeled III corresponds to F^{19} left in its 2.78-MeV level while those labeled I and II each represent clusters of three levels of F^{19}. Meaningful assignment of counts to the 2.78-MeV level peak could not be made at 0° from the second run alone; spectra from other runs are shown in Fig. 3 superposed on the second-run data.

In order to assign counts to the peak III shoulder at forward angles, an area analysis was made by fitting a monoenergetic neutron spectrum from the $D(d,n)He^3$ reaction which yielded neutrons of nearly the same energy as those which left F^{19} in its 2.78-MeV level. The monoenergetic spectrum shapes are shown at the positions of peak III with baselines raised by an amount equal to the estimated summed low-energy tails of peaks I and II. The spectrum shape shown on the 0° data of the second run has been drawn to represent a spectrum shape deduced from all runs at 0° obtained by roughly normalizing the peak III plateau to peaks I and II, and with allowance made for electronic circuit drift just preceding the taking of background data of the second run. The existence of the drift was indicated by gain monitoring at the end of the entire run, but its time of occurrence is not well known. The dashed spectrum on the 0° plot was taken with a large accidental anticoincidence uncertainty. After making the area analysis the data at each angle were averaged together according to the estimated uncertainties.

The angular distribution deduced from the data is shown in Fig. 4 along with Butler-Born approximation theoretical angular distribution taken from Lubitz's tables[18] with $L_p=2$ and $r_0=5.0$ F. The uncertainties in assignment of counts to the 2.78-MeV level at forward angles are appreciably larger than from counting statistics alone, and are due primarily to (1) area analysis, and (2) uncertainty in the measurement of accidental anticoincidences.

IV. DISCUSSION OF RESULTS

The disagreement between the earlier two measurements[3,4] of the $C^{13}(d,n)N^{14}$ ground-state neutron angular distributions can be resolved in favor of an unambiguously $L_p=1$ distribution even at the emulsion measurement bombarding energy. The anomalous angular distribution of that measurement must be ascribed to poor statistical accuracy.

In the language of the review article by Macfarlane and French[1] the reduced width from stripping θ^2 is expressed as a product of two factors: $\theta^2=S\theta_0^2$. The spectroscopic factor S depends only on the initial and final nuclear wave functions, while θ_0^2, the single-particle reduced width, is an undetermined factor expected for the same n and l values of nuclear states to vary only slowly with the excitation energy of the final nucleus. Since values of θ_0^2 are only approximately known, ratios of θ^2 rather than absolute values used to obtain ratio of values of S. These experimental ratios are used to check consistency of assumed excited nuclear state configurations relative to the S value of the ground-state configuration. In j-j coupling the factor S can often be very simply predicted from the number of identical nucleons in a shell equivalent to the particle captured in stripping. The N^{14} ground state and 2.31-MeV level properties are each expected to be predominantly due to two $p_{1/2}$ particles outside a closed $p_{3/2}$ core. Since both the ground state and 2.31-MeV level are predicted to have $S=2$, the ratios of θ^2 should be very nearly unity, and examination of Table I shows this to be the case.

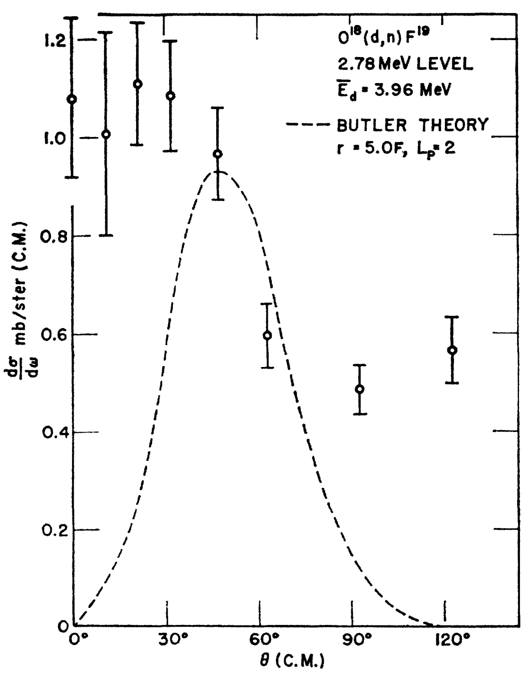

FIG. 4. The angular distribution of neutrons which leave F^{19} in its 2.78-MeV level and deduced from Fig. 1 and auxiliary cross sections. The estimated error in the ordinate scale is $\pm20\%$. The error bars below 450 represent a combined uncertainty and are larger than would be calculated from counting statistics alone.

In extreme j-j coupling and the expected ordering of the N^{14} levels, the reduced width θ^2 for the 3.95-MeV level is zero. This state has been described[2] as $(p_{3/2})^{-1}(p_{1/2})^{-1}$, and should not be created in stripping. As shown in Table I, this level has a reduced width comparable to the ground and 2.31-MeV levels. Auerbach and French[17] have, using the earlier emulsion data,[4] extracted the intermediate coupling constant ρ for this 3.95-MeV level as 3.7 ± 1.5. From the present data the value is 3.9 ± 0.2. There is, by now, already considerable evidence of configuration mixing in the mass 14 isotopes[18,19] which may help explain the large reduced width of the 3.95-MeV level.

The 4.91-MeV level can be assigned $S=1$ since it is considered[2] as a $2s_{1/2}$ nucleon added to the C^{13} ground state. Assigning the values $S=1$ and $S=2$ to the 4.91-MeV level and the ground state, respectively, and then forming the ratio of the θ^2 after factorization of the S values:

$$\theta^2(\text{4.91-MeV level})/\theta^2(\text{ground state}) = \tfrac{1}{2}\theta_0^2(\text{4.91-MeV level})/\theta_0^2(\text{ground state}).$$

Experimentally the θ^2 ratio is about two or a little less. From this experimental value:

$$\theta_0^2(\text{4.91-MeV level})/\theta_0^2(\text{ground state}) \lesssim 4,$$

which seems in reasonable agreement with a ratio of about 3 extracted from Figs. 55 and 56 of reference 1. These later graphs pertain to the value of θ_0^2 as a function of binding energy for $1p$ and $2s$ nucleons. From this analysis the conclusion may be drawn that either the shell-model assignment of the 4.91-MeV level is correct; or else, assuming it correct, the θ_0^2 values are consistent with those on the graphs.

Recently, the level structure of Li^6 and O^{18} have been described in terms of the interactions of two nucleons outside a closed shell core[20,21]; perhaps the description of N^{14} as a neutron and proton outside the stable C^{12} ground-state configuration could be approached similarly.

The $O^{18}(d,n)F^{19}$ data showed no qualitative similarity to an $l=2$ angular distribution. Before a fit to theoretical curves for $l_p=2$ spin-flip stripping from reference 11 could have been made, some modifications in the formulas appear to be required.[22] The data of the present

[17] T. Auerbach and J. B. French, Phys. Rev. **98**, 1276 (1955).
[18] E. Baranger and S. Meshkov, Phys. Rev. Letters **1**, 30 (1958).
[19] H. A. Weidenmüller, Nucl. Phys. **36**, 151 (1962).
[20] P. H. Wackman and N. Austern, Nucl. Phys. **30**, 339 (1962).
[21] J. F. Dawson, I. Talmi, and J. D. Walecka, Ann. Phys. (N. Y.) **18**, 339 (1962).
[22] W. M. MacDonald (private communication).

experiment are not sufficiently clear-cut at the forward angles to permit an unambiguous assignment from simple stripping theory of an L_p value to confirm the low spin value found by the Russian group[1]: either the value $L_p=1$ which would disagree with their parity assignment, or a combination of $L_p=0$ and $L_p=2$ are suggested. On the other hand, a high spin value and appreciable compound nucleus formation cannot be ruled out.

Taking the value of $\frac{1}{2}+$ or $\frac{3}{2}+$ from reference 11 along with the information from a study of the $N^{15}(\alpha,\gamma)F^{19}$ reaction[23] that the spin cannot be $\frac{1}{2}$, then the 2.78-MeV level of F^{19} must be given a $\frac{3}{2}+$ assignment. However, the $N^{15}(\alpha,\gamma)F^{19}$ work favors a high spin value for this level, so the situation is still not completely clear.

Were the level really $\frac{3}{2}+$ and the observed angular distribution a combination of $L_p=0$ and $L_p=2$, the latter corresponding to the principal capture, it is amusing to speculate that the $L_p=0$ contribution corresponds to spin-flip stripping.

Peaks I of Fig. 3 at various angles consist of the unresolved ground state, 110-keV level, and 197-keV level group. Qualitatively, the forward peaking of peaks *I* would suggest that the principal contribution at small angles is from the ground-state group since only this group would give rise to an $l_p=0$ angular distribution. Peaks II correspond to the unresolved 1.35- and 1.46-MeV level groups, and these peaks correspond to an $l_p=1$ angular distribution which suggests that the 1.35- or 1.46-MeV level or both have odd parity.

ACKNOWLEDGMENTS

The authors gratefully acknowledge valuable discussions with Dr. R. van Lieshout. Sincere thanks are due F. Morrison for considerable help in operating the Van de Graaff generator, and to William Lemieux and Richard Heitler for carrying out many of the calculations.

APPENDIX

Remarks About Spectrometer Operation and Accidental Anticoincidence Uncertainty

In the paper describing the gas-recoil fast-neutron spectrometer a formula was derived which permits differential cross sections to be extracted from counts in a peak of the pulse-height distribution. The formula is based on the solid angle of acceptance for proton recoils.[12] In addition, a graphical analysis was made in order to deduce the spectral line shape for monoenergetic neutrons. In practice, the differential cross-section formula has proven relatively valid from comparisons of cross sections obtained by spectrometer measurements with published values for the $D(d,n)He^3$ reaction. The spectral line shape, on the other hand, is always wider than can be accounted for by the combination of the energy-angle dependence of the recoils accepted for measurement with a reasonable spread in pulse heights inherent in proportional counters. In all likelihood the explanation for the breakdown of the geometrical analysis in the case of line shape is due to the assumption of straight recoil tracks. Multiple Coulomb scattering with consequent track curvature would permit tracks concave toward the center wire be accepted for the measurement even though they would have been rejected if straight. Such tracks will give rise to more low-energy pulses than otherwise expected. On the other hand, the formula for extracting cross sections would be relatively correct if, to a first approximation, the recoils which are rejected from measurement because of an outward curvature are equal in number to the overly large angle recoils accepted because of an inward curvature.

The principal uncertainties in the formula for extracting cross sections are probably due to the fact that (1) the effective diameter of the central volume is not precisely the geometrical one but rather depends on the efficiency of the anticoincidence system for detecting proton recoils which penetrate the transparent cathode; (2) the aforementioned assumption of straight tracks; (3) the effective beginning and end of the central volume are not precisely known.

The problem of accidental anticoincidence has proven troublesome in that errors in measurement of accidental anticoincidences can be reflected as much larger errors in cross-section measurement. The principal uncertainty in this measurement arose from the need to keep the beam current the same as during the run; the uncertainty in maintaining constancy of beam current is estimated at 8%. If C_{t+b}= the ratio of 3600 pulser signals per minute to the measured counts in pulser channels when performing the target plus background measurement, with N_{t+b}= the target plus background counts assigned to a peak; and if C_b and N_b are the corresponding quantities for the background measurement; then the net counts $M=C_{t+b}N_{t+b}-C_bN_b$. Considering only statistical uncertainties and those in the C's:

$$\Delta M=[(C_{t+b})^2N_{t+b}+\Delta C_{t+b}N_{t+b}^2+C_b^2N_b+\Delta C_bN_b^2]^{1/2}.$$

It is now necessary to obtain ΔC in terms of ΔI, the beam current uncertainty.

Each $C=3600/A$, where A is the number of pulser signal recorded. A can be expressed as a linear function of beam current I: $A=3600-kI$, with k an undetermined constant. Then

$$\Delta A=-k\Delta I,\quad\text{and}\quad k=(3600-A)/I,$$

$$\begin{aligned}\Delta C&=-(3600/A^2)\Delta A\\&=-(3600/A^2)(-k\Delta I)=-(3600/A^2)\\&\qquad\times[-(\Delta I/I)(3600-A)]\\&=[3600(3600-A)/A^2]\Delta I/I\quad\text{with}\quad \Delta I/I\approx 8\%.\end{aligned}$$

from these relations ΔM can be calculated once A is measured.

[23] P. C. Price, Proc. Phys. Soc. (London) **70**, 661 (1957).