$^{15}N(p, d)^{14}N$ Reaction at 39.8 MeV*

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Energy spectra and angular distributions were obtained for the $^{15}N(p, p)^{15}N$ and $^{15}N(p, d)^{14}N$ reactions at 39.8 MeV. Spectroscopic factors were extracted for the levels in ^{14}N populated by $l_n=1$ pickup and were found to be in excellent agreement with intermediate-coupling predictions, which for this nucleus differ only slightly from j-j coupling. A width of 210±30 keV was measured for the $J^\pi=1^+$, $T=1$ level at 13.72 MeV. Angular distributions for other levels populated in the $^{15}N(p, d)^{14}N$ reaction are shown.

INTRODUCTION

THE availability of protons having energies greater than 30 MeV and high-resolution solid-state detectors in recent years has made possible the use of the (p, d) reaction for studying the spectroscopy of the light nuclei to relatively high excitation energies.[1–4] Some work has been done with 100- and 156-MeV protons,[5,6] although with poor enough resolution to limit studies to the strongly excited levels. In these studies spectroscopic factors have been extracted, mainly by comparison to distorted-wave Born-approximation (DWBA) calculations. Comparisons were then made to intermediate coupling shell-model predictions of the spectroscopic factors, such as those of Cohen and Kurath.[7] In the preceding paper,[4] the problem of extracting meaningful spectroscopic factors using DWBA calculations has been explored. The present paper uses the criteria developed there in an analysis of the $^{15}N(p, d)^{14}N$ reaction. This reaction has been studied previously by Bennett,[8] but the low proton energy (16.5–18.5 MeV) restricted the study to the 0.0-, 2.311-, and 3.945-MeV levels. The results of the present study are also compared to the predictions of Cohen and Kurath.[7]

EXPERIMENTAL PROCEDURE

A ^{15}N target, consisting of a 99% enriched ^{15}N gas maintained at a pressure of 29-cm Hg in a 3-in. cell with a 0.0005-in. Kapton[9] window, was bombarded with 39.89-MeV protons from the Michigan State University sector-focused cyclotron. Correcting for energy losses in the Kapton and gas gives a proton energy at the center of the cell of 39.84 MeV. The resulting deuterons were stopped in a $\Delta E-E$ counter telescope consisting of one 260- and two 2000-μ silicon surface barrier detectors. Mass identification was accomplished by multiplying the ΔE and E signals in a pulse multiplier designed by Miller and Radeka[10] to obtain a product pulse proportional to MZ^2. The elastic protons, which were not stopped by the detectors and thus produced product pulses smaller than those of protons which were stopped, were also detected. Angular distributions were measured between $\theta_{\text{lab}}=\sim10°$ and 142° with an over-all resolution of ~90 keV. The measurement uncertainty in the differential cross sections is estimated to be ~3.6% and was added in quadrature to the statistical uncertainty to obtain the total uncertainty represented by the error bars shown on all data points. A more detailed description of the experimental methods and the treatment of errors is contained in Ref. 11.

ELASTIC SCATTERING DATA AND OPTICAL-MODEL PARAMETERS

The $^{15}N(p, p)^{15}N$ angular distribution obtained is shown in Fig. 1 together with an optical-model fit performed with the Perey search code GIBELUMP.[12] An optical potential of the standard form was used, where W_S is a volume imaginary potential and W_D is a surface imaginary potential. The parameters (given in Table I) are similar to those for proton elastic scattering from ^{16}O at a comparable energy.[4]

For the analysis of the $^{15}N(p, d)^{14}N$ data, optical-model parameters for deuteron elastic scattering on ^{14}N at 32.8 MeV and lower were required. Very few data are

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[12] Unpublished FORTRAN-IV computer code written by F. G. Perey and modified by R. M. Haybron at Oak Ridge National Laboratory.

TABLE I. Optical-model parameters used in the DWBA analysis of the $^{15}N(p, d)^{14}N$ reactions.

Outgoing particle	E (MeV)	V (MeV)	r_R, r_{so} (F)	a_R, a_{so} (F)	W_S (MeV)	W_D (MeV)	r_I (F)	a_I (F)	V_{so} (MeV)
p	39.84	43.9	1.13	0.66	4.54	2.93	1.42	0.48	8.0
d	32.9	93.5	1.02	0.80	0.0	8.70	1.41	0.70	7.57
d	24.8	98.5	1.00	0.80	0.0	7.80	1.46	0.70	7.57
d	17.2	106.0	0.97	0.80	0.0	6.80	1.52	0.70	7.57

available in the literature, and those which are available[13,14] correspond to lower deuteron energies and were analyzed using simplified forms of the optical-model potential. Thus, it was decided to use parameters derived from $^{16}O(d, d)^{16}O$ data, discussed in Ref. 4. Newman *et al.*[15] have shown that the variation of the parameters with Z and A is rather slow, so these parameters should be valid. Table I also lists the deuteron parameters used in the $^{15}N(p, d)^{14}N$ analyses.

EXPERIMENTAL RESULTS

The simplest shell-model configuration for the ^{15}N ground state is that of one $1p_{1/2}$ proton hole in a ^{16}O core. Thus, the neutron configuration should be similar to that of ^{16}O. The spin and parity of the ^{15}N ground state is $\frac{1}{2}^-$, so the pickup of a $1p_{1/2}$ neutron populates ^{14}N states having $J^\pi = 0^+, 1^+$, and the pickup of a $1p_{3/2}$ neutron leads to states having $J^\pi = 1^+, 2^+$. Based upon the simple shell model, using only $1p$ nucleons outside a filled $1s$ core, one can construct the ^{14}N configurations shown in Fig. 2. The isotopic spin quantum number T is good for all of the states shown, the particular combinations of the two terms of diagram (c) being necessary for this reason. The $T=1$ states are those in which a neutron could be transformed into a proton, or vice versa, without violating the Pauli principle. Of the ten possible levels, there are nine which could be reached by $1p$ pickup from ^{15}N, since excitation of the 3^+ level is forbidden by angular momentum conservation. The three other levels having configuration (b) are not populated by a direct pickup in the simplest model since they require the excitation of one of the protons in ^{15}N. Thus, one would expect to see six strong levels (one 0^+, $T=1$; two 1^+, $T=0$; one 1^+, $T=1$; one 2^+, $T=0$; and one 2^+, $T=1$).

There are over 50 known levels in ^{14}N between 0.0 and 14.0 MeV, 18 of which have been identified as 0^+, 1^+, or 2^+ (see Table II). The energies, spins, and parities are taken from Ref. 16 and the references therein, and are consistent with the present results

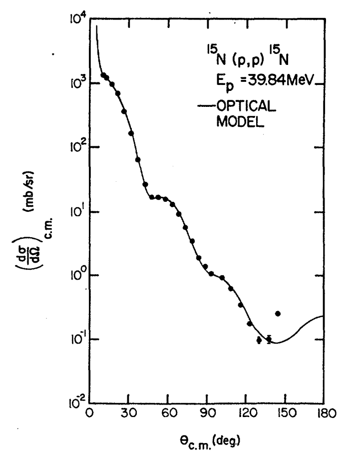

FIG. 1. Optical-model fit to the $^{15}N(p, p)^{15}N$ angular distribution.

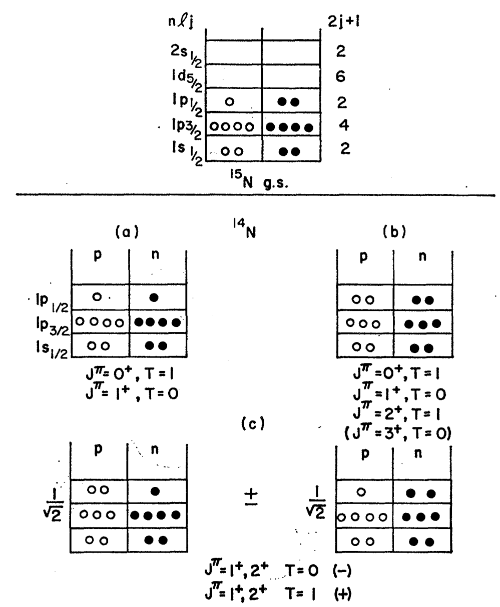

FIG. 2. Simple shell-model configurations of the ^{15}N ground state and the ^{14}N levels based only on $1s$-$1p$ nucleons.

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TABLE II. Peak cross sections and spectroscopic factors for the levels observed in ^{14}N. The average cross section over the indicated angular range is given for weak levels having angular distributions showing no characteristic maximum. The uncertainties quoted in the spectroscopic factors represent only the uncertainties in σ_{peak}.

E_x (MeV)	J^π	T	l_n	σ_{peak} (mb/sr)	θ_{peak} (deg)	$S(p, d)$
0.0	1^+	0	1	11.1±0.8	12 ± 1	1.27±0.09
2.311	0^+	1	1	3.4±0.2	14 ± 1	0.50±0.03
3.945	1^+	0	1	3.3±0.4	14 ± 1	0.60±0.07
4.910	0^-	0	0	0.06±0.02	12− −15	
5.104	2^-	0	2	0.22±0.06	18 ± 2	0.06±0.02
5.685	1^-	0	0	0.12±0.03	12− −15	
5.832	3^-	0	2	0.15±0.05	21 ± 3	0.04±0.01
6.21	1^+	0	1	0.15±0.04	15 ± 2	0.03±0.01
6.44	3^+	0		0.01±0.006	14− −34	
6.70				<0.01		
7.029	2^+	0	1	4.7±0.3	15 ± 1	1.02±0.07
7.40				0.02±0.01	18 ± 3	
7.60				<0.01		
7.97	2^-	0		0.05±0.02	15 ± 2	
8.060	1^-	1	0	0.06±0.03	12− −15	
8.617	0^+	1		0.02±0.01	21 ± 2	
8.906	3^-	1		0.04±0.02	12− −29	
8.963 }	5^+	0				
				0.05±0.02	21 ± 2	
8.979 }	2^+	0				
9.17	2^+	1	1	1.7±0.2	15 ± 1	0.49±0.06
9.388	2^-(?)	0	(3)	0.12±0.05	30 ± 3	0.05±0.02
9.508	2^-	1		0.06±0.02	9− −18	
9.702	1^+	0		0.01	9− −45	
10.096	(1^+)	0	1	0.10±0.03	16 ± 2	0.03±0.01
10.213	1^+	0		0.04±0.02	10− −22	
10.431	2^+	1	1	1.16±0.15	16 ± 1	0.39±0.05
10.85	(4^+)	0		<0.01		
11.06	1^+	0	1	0.09±0.03	16 ± 2	0.04±0.01
11.23 }	(3^-)	1				
				0.05±0.03	15 ± 3	0.02±0.01
11.299 }	2^-	0	(1)			
11.39	(1^+)	0		0.02±0.01	14− −24	
11.51	3^+	0		0.03±0.01	30 ± 3	
11.66				0.05±0.03	12 ± 3	
11.74 }	1^+					
				0.03±0.02	12− −40	
11.80 }	(2^+)					
11.97	2^+			~0.01	10− −30	
12.21 }	3^-					
				0.01±0.01	14− −25	
12.29 }						
12.52			(1)	0.32±0.05	24 ± 3	
12.61	3^+			0.06±0.03	11− −23	
12.80 }	4^+					
				0.07±0.03	11− −30	
12.83 }	4^-					
13.17 }	(0^-, 1^-)	0				
				0.15±0.05	12− −15	
13.23 }						
13.72	1^+	1	1	1.38±0.1	15 ± 1	0.81±0.06

except for the 9.388 level. An energy-level diagram of ^{14}N, displayed beside a deuteron energy spectrum obtained at $\theta_{\text{lab}}=19.9°$ for an incident proton energy of 39.84 MeV, is shown in Fig. 3. It is seen that many levels are excited; however, the strongly excited levels are seen to be either 0^+, 1^+, or 2^+.

Experimental angular distributions for the ten strongest levels exhibiting the characteristics of $l_n=1$ transfer, are shown in Figs. 4 and 5. J dependence is seen in the steeper slope of the 0^+ angular distribution ($p_{1/2}$ pickup) as compared to the 2^+ angular distributions ($p_{3/2}$ pickup). A Q-dependent effect is seen in the decreasing slopes of the 2^+ angular distributions with increasing excitation energy, as shown in Fig. 5. The slopes of the 0.0 MeV, 1^+ and the 2.311 MeV, 0^+ angular distributions shown in Fig. 4 are very nearly the same, indicating, on the basis of J dependence, that the ground state is populated mainly by $1p_{1/2}$ pickup, as one would expect from energy and model considerations. The other 1^+ angular distributions exhibit less steep slopes, indicating $1p_{3/2}$ pickup. The ^{15}N(p, d)^{14}N and ^{16}O(p, d)^{15}O $l_n=1$ angular distributions[4] are very similar.

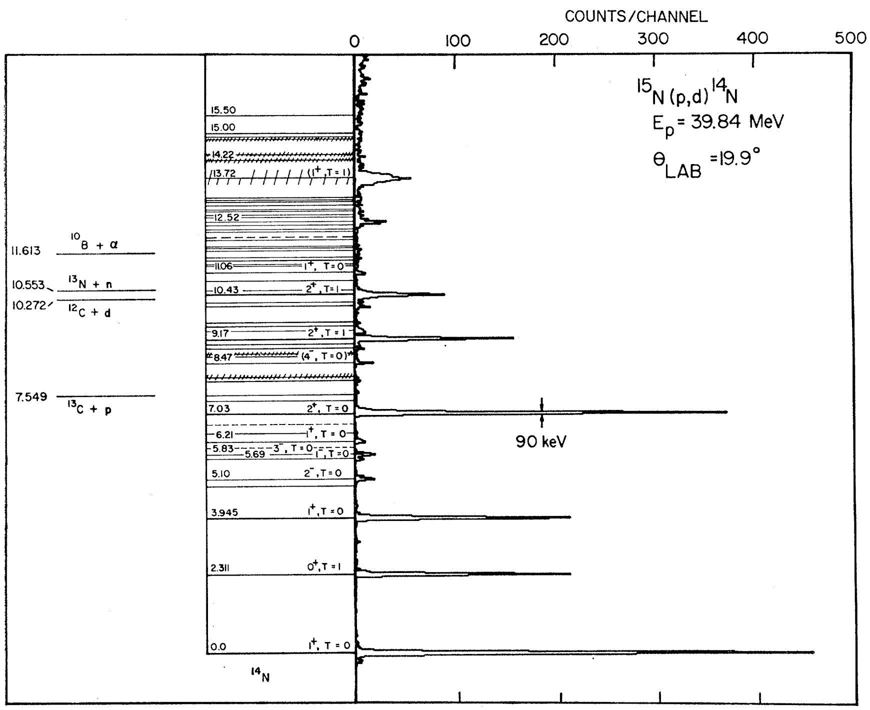

FIG. 3. Energy-level diagram of ^{14}N displayed beside a deuteron energy spectrum from the ^{15}N$(p, d)^{14}$N reaction for $E_p=39.84$ MeV and $\theta_{\text{lab}}=19.9°$.

The broad level at 13.72 MeV had been identified as a 1^+, $T=1$ level by Ball and Cerny[17] from a study of the ^{15}N$(^3$He$, \alpha)^{14}$N neutron pickup reaction. The present results confirm this assignment and yield a width for this level of 210 ± 30 keV. Ball and Cerny also found almost equal excitation of the 9.17- and 10.43-MeV levels, as was found in the present work. Angular distributions for other levels excited are shown in Fig. 6. These levels are weakly excited, and their angular distributions do not contradict the assignments in Table II.

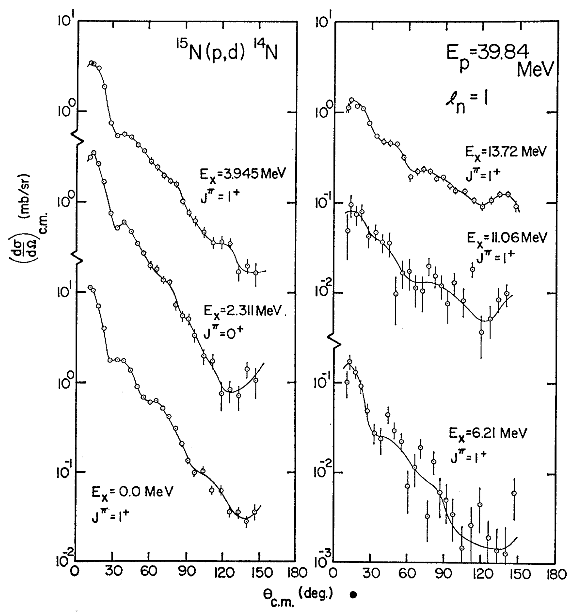

FIG. 4. Experimental deuteron angular distributions for the 0^+ and 1^+ levels of ^{14}N strongly excited in the ^{15}N$(p, d)^{14}$N reaction for $E_p=39.84$ MeV. The solid lines are drawn to guide the eye.

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

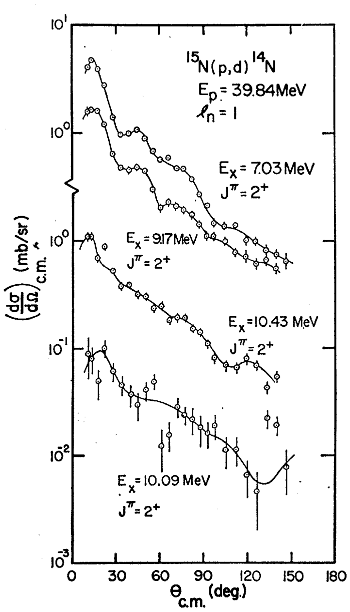

FIG. 5. Experimental deuteron angular distributions for the 2^+ levels of ^{14}N strongly excited in the ^{15}N$(p, d)^{14}$N reaction for $E_p=39.84$ MeV. The solid lines are drawn to guide the eye.

The excitation of levels other than 0^+, 1^+, or 2^+ in the (p, d) reaction is an indication of admixtures in the ground state of ^{15}N, the most likely ones being $1d_{5/2}$ and $2s_{1/2}$, leading to excitation of 2^- or 3^- and 0^- or 1^- states, respectively. Most are very weakly excited. The level at 12.52 MeV had no previous assignment and is rather strongly excited, especially for a state with such a high excitation energy. Its angular distribution is most consistent with $1p$ pickup. The angular distribution of the 9.39-MeV level shows a rather broad maximum around 30° so that $l_n=3$ or possibly 4 might be preferred, which would disagree with the 2^- assignment for the state.

Levels assigned $J^\pi=3^+$ or 4^+ would require $1f$ neutron pickup in the direct reaction picture. The angular distributions for the 12.61- and 12.80-MeV levels may contain contributions from other close-lying levels. Again, the cross sections are small. The existence of a level between the 10.55- and 11.06-MeV levels has been reported at 10.71,[18] at 10.81,[16] and at 10.85 MeV.[19,20]

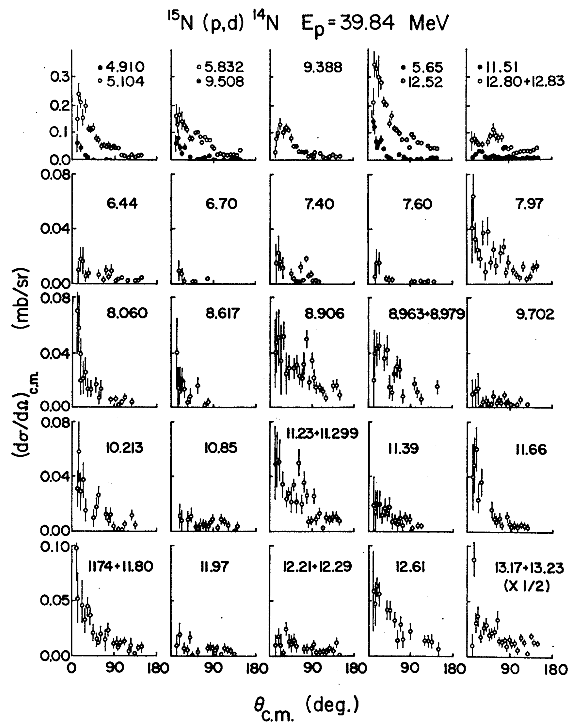

FIG. 6. Deuteron angular distributions for the ^{14}N levels not shown in Figs. 4 and 5 excited by the $^{15}N(p, d)^{14}N$ reaction for $E_p=39.84$ MeV.

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

[19] B. G. Harvey, J. R. Merriwether, and J. Mahoney, Phys. Rev. **146**, 712 (1966).

[20] R. H. Bassel, R. M. Drisko, and G. R. Satchler, Oak Ridge National Laboratory Report No. ORNL-3240, 1962 (unpublished); R. H. Bassel, R. M. Drisko, and G. R. Satchler, Oak Ridge National Laboratory Memorandum to the Users of the Code JULIE, 1966 (unpublished).

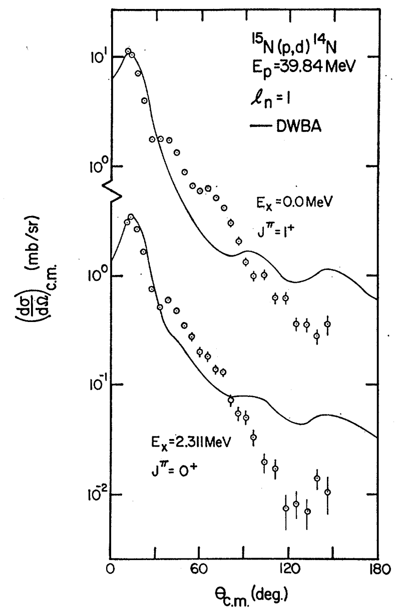

FIG. 7. DWBA calculations for the $^{15}N(p, d)^{14}N$, $E_p=39.84$ MeV, $E_x=0.0$- and 2.311-MeV angular distributions.

An assignment of $J^\pi=4^+$, $T=0$ has been made by Mangelson *et al.*[16] In the present work a very weakly excited level was found at 10.80 ± 0.05 MeV. The angular distribution is shown in Fig. 6. Several other levels were weakly excited, and their angular distributions are shown in Fig. 6. The peak cross sections, and where applicable, l_n values for all levels excited in the $^{15}N(p, d)^{14}N$ reactions are listed in Table II.

DWBA ANALYSES AND COMPARISON TO THEORY

The results of the study of the extraction of spectroscopic factors for the $^{16}O(p, d)^{15}O$ reaction have been applied in the present work. DWBA calculations were performed with the code JULIE[20] using a lower radial integration cutoff of 3 F and a bound-state well radius equal to the proton real-well radius. Figure 7 shows the results of the DWBA calculations for the first two $l_n=1$ levels, while Fig. 8 shows a calculation for one of the $l_n=2$ levels excited, representing a $1d_{3/2}$ admixture in the ^{15}N ground state. Spectroscopic factors were extracted by matching the experimental and calculated angular distributions at the characteristic first maximum. A discussion of this procedure is also given in Ref. 4. Table II contains a list of the spectroscopic factors extracted, the errors quoted reflecting only the error in the experimental peak cross section. The decision as to whether a 1^+ level was formed by $1p_{1/2}$ or $1p_{3/2}$ pickup was made on the basis of the shape of the angular distribution (J dependence) and on the predictions of Cohen and Kurath.[7] The total $1p$ strengths seen in this reaction are

$$\sum S(1p_{1/2})=1.77, \qquad \sum S(1p_{3/2})=3.41$$

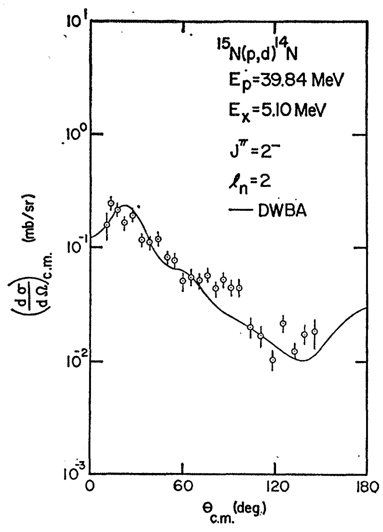

FIG. 8. DWBA calculation for the ^{15}N(p, d)^{14}N, E_p=39.84 MeV, E_x=5.10-MeV angular distributions.

giving $\sum S(1p)=5.18$. Thus we see approximately 10% more of the $1p_{3/2}$ strength than was observed in the ^{16}O(p, d)^{15}O reaction.[4] Excluding 0^- states, the amount of $2s$-$1d$ admixture in the ^{15}N ground state is given by $\sum S(2s-1d)=0.17$, again comparable to that found in the ^{16}O(p, d)^{15}O reaction. Hence we see about 90% of the total expected spectroscopic factor of 6.

The predictions of the intermediate coupling model of Cohen and Kurath[7] are given in Table III; they show six strong levels below 12.0 MeV, with three weak levels lying at higher excitation levels. Included in Table III are the spectroscopic factors expected in the jj-coupling limit. Pickup of a $1p_{1/2}$ neutron leads to states having configuration (a) in Fig. 2 whereas $1p_{3/2}$ pickup leads to states having configuration (c). It is seen that for the ^{15}N(p, d)^{14}N reaction the jj-coupling and intermediate-coupling descriptions are very similar.

A graphical comparison of the theoretical and experimental results is given in Fig. 9, where the lengths of the lines are proportional to the spectroscopic factors. The extensions of the theoretical lines represent the jj-coupling predictions. Seven strong levels were observed in the present experiment, all of which have angular distributions characteristic of $l_n=1$ pickup, whereas the Cohen and Kurath calculations predict only six levels. It appears that the $1p$ strength in the 2^+, $T=1$ level predicted to be at 9.524 MeV is shared by the 2^+, $T=1$ level at 10.43 MeV, a conclusion also reached by Ball and Cerny from their ^{15}N(^{3}He, α)^{14}N work.[17] The mixing of these levels is supported by the values of the $M1$ transition strengths of the (9.17-MeV–0.0-MeV) and (10.43-MeV–0.0-MeV) transitions. Warburton and Pinkston[21] indicate that a single 2^+, $T=1$ level having a $(1s)^4(1p)^{10}$ configuration is allowed in the 10-MeV region (the one predicted by both jj coupling and intermediate coupling). A 2^+, $T=1$ level having a $(1s)^4(1p)^8(1s)(1d)$ configuration is expected in the same region. The predictions for the relative $M1$ strengths for ground-state transitions from these levels are 12 and 0, respectively. Since the observed $M1$ strengths for the 9.17- and 10.43-MeV ground-state transitions are 4.1 and 5.5, respectively, Warburton and Pinkston[21] suggest that these two levels are mixtures of the two configurations. The ratio of the $(1s)^4(1p)^{10}$ components of the two levels is given by the ratio of the $M1$ strengths and can be obtained from the present work as the ratio of the $1p$ spectroscopic factors for these levels. These ratios are

$$[(1s)^4(1p)^{10},\ (9.17\text{ MeV})]/[(1s)^4(1p)^{10},\ 10.43\text{ MeV})]=0.75$$

from the $M1$ strengths, while from the present (p, d) experiment we get

$$[(1s)^4(1p)^{10},\ (9.17\text{ MeV})]/[(1s)^4(1p)^{10},\ (10.43\text{ MeV})]=1.25\pm0.15.$$

Thus, both the work of Warburton and Pinkston[21] and the present work suggest strong mixing of the two levels, but disagree somewhat about the division of $1p$ strength between them. The sum of the spectroscopic factors for the 9.17- and 10.43-MeV levels is slightly less than that predicted for the 9.524-MeV level, but the over-all

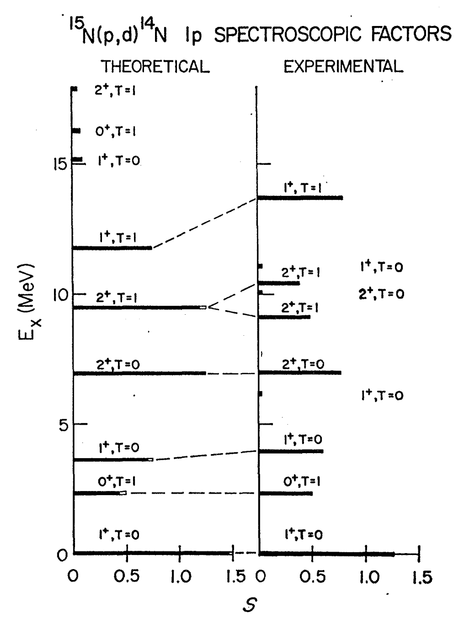

FIG. 9. Theoretical and experimental $l_n=1$ spectroscopic factors for the ^{15}N(p, d)^{14}N reaction.

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

TABLE III. Intermediate-coupling predictions of coefficients of fractional parentage and spectroscopic factors for $1p$ neutron pickup from ^{15}N. Also included are the spectroscopic factors predicted in jj coupling.

E (calc.) (MeV)	(J^{π}, T)	nlj	CFP	$\sum_i CFP^2$	S	S_{jj}
0.0	$(1^+, 0)$	$1p_{3/2}$	0.0542			
		$1p_{1/2}$	−0.3601	0.1326	1.459	1.500
2.690	$(0^+, 1)$	$1p_{1/2}$	0.3376	0.1140	0.418	0.500
3.616	$(1^+, 0)$	$1p_{3/2}$	0.2434			
		$1p_{1/2}$	0.0642	0.0633	0.696	0.750
6.991	$(2^+, 0)$	$1p_{3/2}$	−0.3371	0.1136	1.250	1.250
9.524	$(2^+, 1)$	$1p_{3/2}$	−0.5704	0.3255	1.192	1.250
11.783	$(1^+, 1)$	$1p_{3/2}$	−0.4523			
		$1p_{1/2}$	0.000	0.2046	0.750	0.750
15.238	$(1^+, 0)$	$1p_{3/2}$	−0.0776			
		$1p_{1/2}$	−0.0505	0.0086	0.095	0.000
16.323	$(0^+, 1)$	$1p_{1/2}$	0.1497	0.0224	0.082	0.000
17.879	$(2^+, 1)$	$1p_{3/2}$	−0.1246	0.0155	0.057	0.000

agreement is good. These data thus support the 2^+, $T=1$ assignments for the 9.17- and 10.43-MeV levels. The several weakly excited $l_n=1$ levels observed in the present experiment probably result from small admixtures of the wave functions of the strong levels having the same J^{π} and T. No levels of measurable strength were observed above 13.72 MeV. The three weak levels predicted by Cohen and Kurath probably appear at much higher excitation energies and may be mixed with other levels. The strongest of these levels would be expected to have a peak cross section of only 50 μb/sr, and since the levels are well above the particle threshold and therefore expected to be broad, there would be little hope for being able to separate them from the background. The excellent over-all agreement of the Cohen and Kurath intermediate-coupling predictions and the experimental spectroscopic factors is further evidence for the validity of this model for $1p$-shell nuclei.

ACKNOWLEDGMENTS

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