Structure of ^{15}N and the $^{14}N(d, p)^{15}N$ Reaction*

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Angular distributions have been measured for the $^{14}N(d, p)^{15}N$ reaction to levels up to 10.80-MeV excitation in ^{15}N. Distorted-wave Born-approximation fits have been obtained to most of these levels and absolute spectroscopic factors have been extracted. Although the spectroscopic factors for the low-lying $\frac{5}{2}^+$, $\frac{1}{2}^+$ doublet at 5.27, 5.30 MeV are very small, those for the next four positive-parity levels are close to the single-particle value of 1. To explain these features a weak-coupling model is proposed, in which an $s_{1/2}$ or $d_{5/2}$ particle is coupled to a core corresponding to the 1^+, $T=0$ ground state of ^{14}N or to the 0^+, $T=1$ first excited state. Explicitly included in the model is the splitting due to the $\mathbf{T}\cdot\mathbf{t}$ force, which accounts for the low-lying position of the $\frac{5}{2}^+$, $\frac{1}{2}^+$ doublet.

I. INTRODUCTION

A. Low-Lying Positive-Parity States in ^{15}N

THE ^{15}N nucleus has been studied extensively, since its structure is of considerable interest in the framework of the shell model.[1,2] The $\frac{1}{2}^-$ ground state and the $\frac{3}{2}^-$ level at 6.32 MeV can be interpreted simply as $p_{1/2}$ and $p_{3/2}$ holes in the ^{16}O closed shell.[3] Less simply understood are the low-lying states of unnatural (positive) parity, which may be grouped into two multiplets:

1. A doublet of states at 5.27 and 5.30 MeV with $J=\frac{5}{2}^+$ and $\frac{1}{2}^+$, respectively.
2. Five positive-parity levels between 7.15 and 8.57 MeV. This division serves to emphasize the relative depression of the 5.3-MeV doublet, which is almost 2 MeV below group 2, although the average separation of the levels within group 2 is only 0.35 MeV.

Theoretical efforts on ^{15}N have aimed largely at explaining the characteristics of these two groups of positive-parity states. The unnatural parity implies excitations into the *s-d* shell. Lane[4] has considered a weak-coupling model in which an $s_{1/2}$ or $d_{5/2}$ particle is coupled to the 1^+, $T=0$ ground state of ^{14}N or to the 0^+, $T=1$ first excited state at 2.31 MeV, giving seven levels with the correct spins and parities, corresponding to those observed. The most serious difficulty with this model was the lack of an explanation for the low-lying position of the 5.3-MeV doublet (see Fig. 1). At the next level of sophistication, Halbert and French[5] have used single-particle configurations, in which a *p*-shell nucleon is promoted into the *s-d* shell, as a basis for an individual-particle-model (IPM) calculation. Again, they obtained seven low-lying levels with the correct spins and parities. They found each level to have predominantly a 2*s* or 1*d* character, in agreement with the weak-coupling picture. However, serious disagreement involved the considerable mixing of configurations with a $T=0$ core and those with a $T=1$ core. As seen in Fig. 1, this core-configuration mixing tends to spread apart the levels of the same J_f and does result in a low-lying $\frac{5}{2}^+$ state. However, the lowest-$\frac{1}{2}^+$ state is still too high, and the resulting general level density is too low. Nevertheless, calculations using these wave functions have been generally successful in comparisons to experimental neutron reduced widths obtained from plane-wave (d, p) stripping studies.[5] Because of the lack of good single-particle reduced widths, however, these are only relative comparisons.

In the present experiment we have obtained absolute spectroscopic factors from distorted-wave Born-approximation (DWBA) fits to the measured $^{14}N(d, p)^{15}N$ stripping cross sections. The resulting spectroscopic factors are quite small for the 5.3-MeV doublet, but are nearly unity for four of the five levels in group 2, which is significantly larger than the IPM predictions. This implies a strong single-particle character for these levels and has led us to reconsider the weak-coupling model first suggested by Lane. With the inclusion of the action of the $\mathbf{T}\cdot\mathbf{t}$ force, which Lane himself later proposed in connection with isobaric analog states,[6] most of the known features of these levels are reproduced satisfactorily, *including the position of the 5.3-MeV doublet.*

B. Levels above 9 MeV in ^{15}N

Above 9 MeV the level structure of ^{15}N becomes more complex. Theoretical calculations are increasingly difficult because of the number of higher-order configurations which must be included at these energies, and there have remained important gaps in the experimental knowledge of spins and parties for levels in this region. In earlier studies, the 9.05-, 9.16-, and 9.22-MeV levels often were not resolved. Now it is apparent that the 9.16-MeV level is, in fact, a very close-lying doublet.[7]

* Research supported in part by the U.S. Atomic Energy Commission.

[1] G. W. Phillips, F. C. Young, and J. B. Marion, Phys. Rev. **159**, 891 (1967). Reviews of the literature on ^{15}N can be found in this and Ref. 2.
[2] E. K. Warburton, J. W. Olness, and D. E. Alburger, Phys. Rev. **140**, B1202 (1965).
[3] D. Kurath, Phys. Rev. **101**, 216 (1956).
[4] A. M. Lane, Rev. Mod. Phys. **32**, 519 (1960).
[5] E. C. Halbert and J. B. French, Phys. Rev. **105**, 1563 (1957).
[6] A. M. Lane, Nucl. Phys. **35**, 676 (1962).
[7] C. E. Steerman and F. C. Young, Phys. Letters **27B**, 8 (1968).

For higher-energy levels earlier experiments sometimes gave ambiguous or even contradictory spin-parity assignments.

Recent particle–γ-ray angular correlation studies have been successful in determining the spin or limiting the possible spins for levels in this region,[1,8] but such correlations are independent of the parity of the levels involved. On the other hand, (d, p) stripping results can give clear l-value assignments for the transfer of orbital angular momentum, thus determining the change in parity as $(-1)^l$. However, it is much more difficult to distinguish between transitions with the same l transfer but to levels with different spins. Stripping and correlation studies thus yield complementary information about nuclear levels, a feature which until recently has not been fully exploited in nuclear-structure studies. In the present experiment, $^{14}N(d, p)^{15}N$ stripping cross sections have been obtained from levels in the region below the neutron binding energy at 10.83 MeV. DWBA fits to the angular distributions have confirmed or established l-transfer values for transitions to several of the levels in this region. These fits, combined with other results, in come cases allow unambiguous determination of spin and parity.

II. EXPERIMENTAL PROCEDURE

$^{14}N(d, p)^{15}N$ angular distributions were measured at 2.5° intervals from approximately 15° to 60° in the laboratory and at incident deuteron energies of 7, 8, and 9 MeV, using the deuteron beam from the HVEC FN tandem accelerator at the Nuclear Physics Laboratory of the University of Washington. Various targets of adenine or melamine evaporated onto thin gold or carbon foils were used in order to minimize interference with the nitrogen peaks of interest from reactions with other components of the target. The usable beam was counting-rate limited at forward angles and was not allowed to exceed 30 nA on target in order to avoid target deterioration. Because both melamine and adenine contain equal amounts of nitrogen and hydrogen, the measured cross sections could be checked by comparing the yield of protons from deuteron scattering on hydrogen with previous measurements.[9] Agreement was within experimental error, but since the previous measurements were more accurate (~5%), they were used for absolute normalization of the present data. Where the measurements overlap, agreement is reasonable between the present results and the previous (d, p) measurements of Green and Middleton[10] at 9.MeV incident energy.

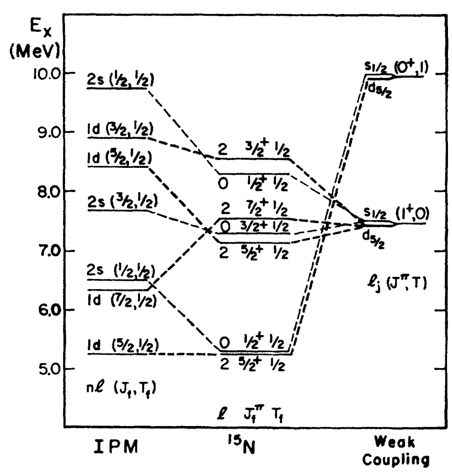

FIG. 1. Comparison of the low-lying positive-parity levels of ^{15}N (center) with the theoretical levels of Halbert and French (Ref. 5) on the left (IPM) and the levels derived from a weak-coupling model based on the proposal by Lane (Ref. 4) on the right, in which an $s_{1/2}$ particle ($l=0$) or a $d_{5/2}$ particle ($l=2$) is coupled to a core corresponding to the $(1^+, 0)$ ground state of ^{14}N, normalized here to the center of mass of the 7–9-Mev levels, or to the $(0^+, 1)$ first excited state, shown higher by 2.3 MeV, its excitation energy in ^{14}N. The $s_{1/2}$-$d_{5/2}$ splitting is taken to be nearly degenerate, as indicated by the mean value of the splitting in $^{17}O(+0.87$ MeV) and in $^{13}C(-0.78$ MeV). The large depression of the 5.3-MeV doublet is evident.

The reaction particles were detected with a ΔE-E telescopic counter array consisting of a thin, 50-μ transmission detector followed by a 1000-μ detector to stop the particles.[11] With this array, protons from about 2.5–11.5 MeV could be detected and identified. Particle identification was achieved by two methods. However, most of the data were taken with a conventional multiplier circuit.[12] Using this circuit, separation between the protons and deuterons was not complete. There was a troublesome background in the proton spectrum, on account of "leak-through" of elastic deuterons, particularly at angles less than 30°. This problem was eliminated by the use of an exponential identifier system,[13] which achieved practically complete particle separation, with a valley-to-peak ratio typically smaller than 10^{-3} between the proton and deuteron groups in the identifier spectrum. This system was used to check and extend the angular distributions at forward angles. To obtain an energy spectrum the pulses from the E and ΔE detectors were added. The sum-energy pulse and the identifier pulse then were fed through analog-to-digital converters (ADC's) to an on-line SDS 930 computer, which sorted and accumulated the energy pulses into proton and deuteron pulse-height spectra according to present windows, which could be monitored during the run, on the respective groups in the identifier spectrum. Periodically the spectra were read out and stored on magnetic tape for later analysis.

The proton spectrum obtained at 30° by using the

[8] E. K. Warburton and J. W. Olness, Phys. Rev. **147**, 698 (1966).

[9] J. C. Allred, A. H. Armstrong, R. O. Bondelid, and L. Rosen, Phys. Rev., **88**, 433 (1952); see also references therein.

[10] T. S. Green and R. Middleton, Proc. Phys. Soc. (London) **A69**, 28 (1955).

[11] Fully depleted silicon surface-barrier detectors were used, obtained from ORTEC, Oak Ridge, Tenn.

[12] V. Radeka, IEEE Trans. Nucl. Sci. **11**, 302 (1964).

[13] F. Goulding, D. Landis, J. Cerny, III, and R. Pehl, IEEE Trans. Nucl. Sci. **11**, 388 (1964).

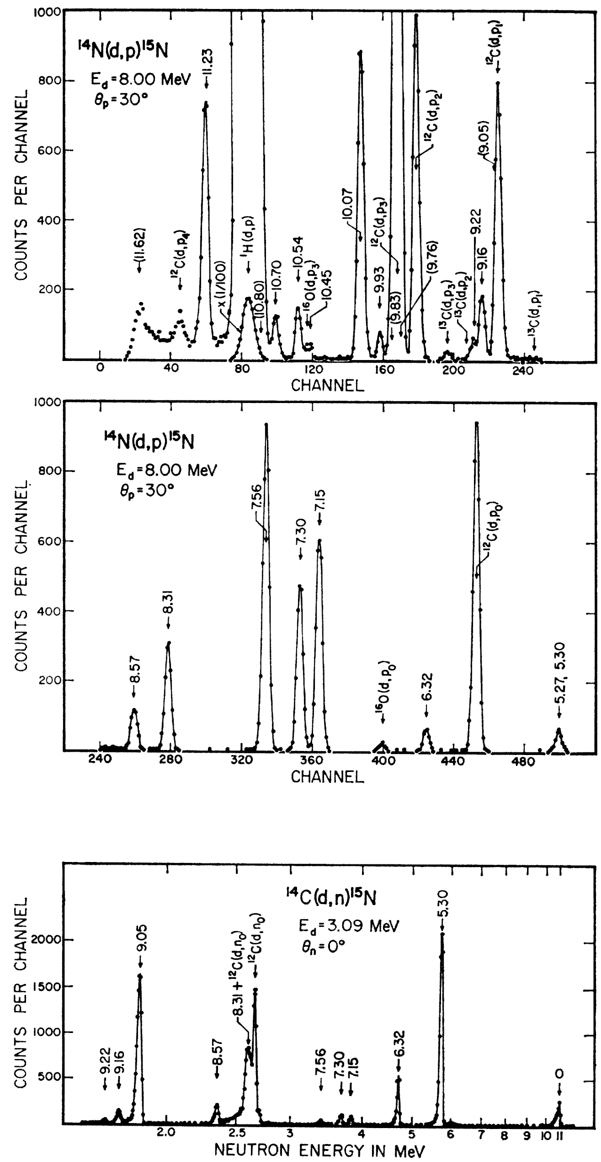

FIG. 2. Proton spectrum from the $^{14}N(d, p)^{15}N$ reaction observed at 30° and 8-MeV incident energy in the present experiment (upper two panels). Also shown for comparison (bottom panel) is the $^{14}C(d, n)^{15}N$ spectrum at 0° and 3-MeV incident energy obtained by Lawergren and Mitchell (Ref. 14).

exponential identifier system is shown in the upper two panels of Fig. 2, with the peaks labeled according to their final-state excitation energy in ^{15}N. Also indicated are proton peaks from the $^{12,13}C$ component of the target and from ^{16}O contamination. For comparison, the bottom panel in the figure shows the neutron spectrum obtained by Lawergren and Mitchell[14] for the $^{14}C(d, n)^{15}N$ reaction to the same final states in ^{15}N. This spectrum will be discussed further in Sec. V.

[14] B. Lawergren and I. V. Mitchell, Nucl. Phys. **A98**, 481 (1967).

III. THEORETICAL FITS

A. Calculation of DWBA and Compound-Nucleus Cross Sections

DWBA fits to the angular distributions were obtained by using the computer code TSALLY[15] with the parameters shown in Table I. The proton optical-model parameters were extrapolated from a study by Perey for heavier nuclei.[16] The calculations are mainly sensitive to the deuteron optical-model parameters. However, no consistent set was available. The parameters obtained in a study by Smith and Ivash[17] of (d, p) stripping in the light nuclei show large and unsystematic variations, as do those reported[18–20] in other stripping and pickup experiments on or near ^{15}N. Therefore, these parameters were used as initial sets and, subsequently, the real and imaginary potential-well depths were varied to obtain the best fits simultaneously to the angular distributions at 8-MeV incident energy for the strongly excited levels, at 7.15 and 7.56 MeV ($l=2$), and at 7.30 MeV ($l=0$). The resulting best set was chosen from about 30 trials and was subsequently used in fitting all the experimental cross sections, with generally satisfactory results over the wide range of l values, excitation energies, and incident energies represented (Figs. 3 and 4).

To fit the cross sections for the more weakly excited levels, it is necessary to include a compound-nucleus contribution obtained from a Hauser-Feshbach type of calculation.[21,22] However, the absolute normalization is generally overestimated in such a calculation, since it

TABLE I. Optical-model parameters.[a]

	d	p
V (MeV)	91.2	48.3
r_0 (F)	1.4	1.25
a (F)	0.7	0.65
W (MeV)	20.0	7.0
r_{0I} (F)	1.4	1.25
a_I (F)	0.7	0.47

[a] A Woods-Saxon form factor was used for the real potentials V and the deuteron imaginary potential W, with parameters r_0, a and r_{0I}, a_I, respectively. For the proton imaginary potential, a differentiated Woods-Saxon form factor was used.

[15] R. H. Bassel, R. M. Drisko, and G. R. Satchler, Oak Ridge National Laboratory Report No. ORNL-3240, 1962 (unpublished).
[16] F. G. Perey, Phys. Rev. **131**, 745 (1963).
[17] W. R. Smith and E. V. Ivash, Phys. Rev. **131**, 304 (1963).
[18] A. Gallman, P. Fintz, and P. E. Hodgson, Nucl. Phys. **82**, 161 (1966).
[19] P. Fessender and D. R. Maxson, Phys. Rev. **158**, 948 (1967).
[20] J. B. Nelson and W. R. Smith, Nucl. Phys. **A96**, 671 (1967).
[21] W. Hauser and H. Feshbach, Phys. Rev. **87**, 366 (1952).
[22] A. A. Katsanos, Argonne National Laboratory Report No. ANL-7289, 1967 (unpublished).

TABLE II. $^{14}N(d, p)^{15}N$ spectroscopic factors.

E_x (MeV)	E_d / l	7 MeV[a]	8 MeV[a]	9 MeV[a]	Mean[a]	IPM[b]	Weak coupling[c]
5.27	2	0.003±0.05	···	0.02±0.06	0.01±0.04	0.134	0.0
5.30	2					0.033	0.0
	0	···	0.01±0.02	···	0.01±0.02	0.110	0.0
6.32	1	0.12±0.02	0.08±0.02	0.11±0.02	0.10±0.02	d	
	CN factor	0.54±0.05	0.44±0.09	0.36±0.05			
7.15	2	0.92±0.02	0.82±0.02	0.90±0.02	0.88±0.03	0.622	1.0
7.30	0	0.88±0.05	0.92±0.10	0.92±0.13	0.89±0.04	0.642	1.0
	2	0.04±0.09	0.13±0.15	0.10±0.18	0.07±0.05	0.015	0.0
7.56	2	0.86±0.02	0.85±0.02	0.89±0.02	0.87±0.01	0.726	1.0
8.31	0	1.01±0.05	1.16±0.06	0.99±0.06	1.02±0.04	0.853	1.0
	2	0.03±0.10	0.04±0.10	0.03±0.09	0.03±0.06	0.005	0.0
8.57	0	0.01±0.03	0.02±0.02	0.04±0.04	0.02±0.01	0.013	0.0
	2	0.12±0.05	0.12±0.04	0.12±0.05	0.12±0.03	0.594	1.0

[a] Error limits are experimental; the theoretical uncertainty in the spectroscopic factor is estimated at about 10% (see Sec. III B).
[b] References 5 and 25.
[c] Extreme single-particle values.
[d] See Table III.

depends on an accurate accounting of all the allowed exit channels from the compound nucleus. Such an overestimate will be larger at higher incident energies, because exit channels open up to higher final-state excitation energies, where the level structure is less known. The normalization therefore was determined by a least-square fit to the angular distributions for the level at 6.32 MeV ($l=1$). As shown in Fig. 3, the direct contribution (DWBA) is largest at forward angles, but the compound-nucleus cross section (CN) dominates beyond about 40°. The normalization factors obtained (Table II) follow the expected trend with incident energy and were used consistently for all the levels observed, although for the stronger levels, the CN contribution is too small to appear on Figs. 3 and 4.

Because a spin-1 target was used, the l transfer to a level in ^{15}N with a given spin and parity is generally not unique. According to the shell model, both terms with $l=0$ and 2 would be expected to contribute to positive-parity levels of spin $\frac{1}{2}$ or $\frac{3}{2}$, and both $l=1$ and 3 could contribute to higher $\frac{3}{2}^-$ or $\frac{5}{2}^-$ levels. Finally, since the 9.16-MeV level is a doublet and may have mixed parity, all l values from 0 to 3 could contribute. In such cases, least-square fits to the experimental cross sections were obtained, including contributions from all l-transfer values consistent with the shell model and the known properties of the level. Where more than one l value is significant, each contribution is indicated on Figs. 3 and 4.

B. Spectroscopic Factors

The spectroscopic factors obtained from a fit of the DWBA cross sections to the data, after subtracting the compound-nucleus contribution, are given in Table II. The spectroscopic factor S is defined in terms of the experimental cross section $d\sigma/d\Omega$ and the DWBA cross section σ_{DWBA} by

$$\frac{d\sigma}{d\Omega}=1.5S\,\frac{2J_f+1}{2J_i+1}\,\sigma_{DWBA},$$

where J_i and J_f are the initial (target) and final-state spins, respectively. The factor of 1.5 is appropriate for the use of Hülthen wave functions.[15] The uncertainties obtained for S are propagated from the experimental uncertainties in the data points, as shown by the error bars in the Figs. 3 and 4. These include statistics and estimated uncertainties due to background subtraction. The probable systematic error in the absolute normalization of the cross sections is less than 5% (see Sec. II). In addition, there is an uncertainty in the DWBA cross sections which depends on the optical-model parameters used. In the present study, reasonably good fits to the angular distributions for the 7.15-, 7.30-, and 7.56-MeV levels at 8-MeV incident energy were obtained for variations of ±5 MeV in the real potential-well depth and ±10 MeV in the imaginary potential-well depth from the values adopted for the deuteron parameters. Over this range of variation, spectroscopic factors

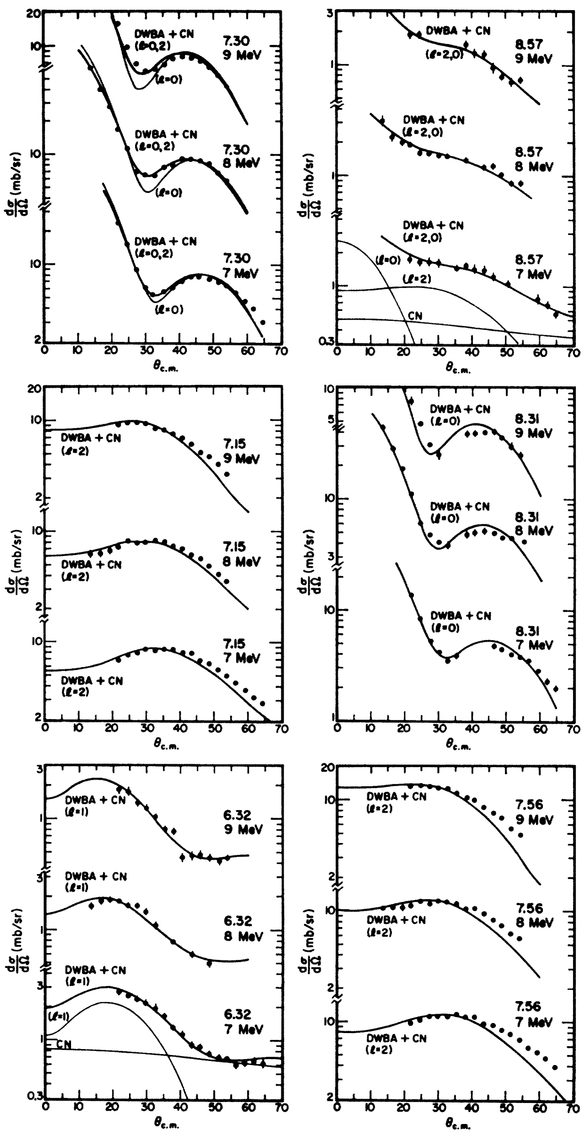

FIG. 3. $^{14}N(d, p)^{15}N$ angular distributions measured for levels from 6.32 to 8.57 MeV in ^{15}N, labeled by the final-state excitation energy (in MeV) and the incident energy. Also shown are the results of the DWBA plus CN fits to the data, as explained in the text. In some cases where more than one component of the fit is important, each separate component is indicated (light lines) as well as the composite fit (heavy line) determined by a least-squares fitting procedure.

consistent to within $\pm 10\%$ were obtained. Thus, the over-all uncertainty in the spectroscopic factors for the strongly excited levels is 10–15%.

IV. RESULTS AND DISCUSSION

A. 5.27-, 5.30-MeV Doublet

The (d, p) cross section to these two unresolved levels was very weak and could be accounted for in full by the compound-nucleus term. Within the uncertainties involved, the upper limits for the $l=0$ and $l=2$ spectroscopic factors are significantly *smaller* than the IPM predictions of 11 and 17%, respectively (see Table II).

B. 6.32-MeV Level

The spectroscopic factors obtained for this level agree within experimental error at all three incident energies (Table II). Since they are the result of a least-squares fit for the spectroscopic factor and the compound-nucleus normalization factor, which varies considerably with incident energy, this agreement adds confidence in the procedure used. However, the experimental spectroscopic factor is about five times larger than predicted by the IPM calculations of Cohen and Kurath.[23] This discrepancy is much larger than that observed for any other well-established $1p$ level in a (d, p)-stripping study by Schniffer *et al.*,[24] who found general agreement throughout the p shell to the predicted spectroscopic factors. In particular, they found the ^{15}N ground-state spectroscopic factor to be 0.84 times the theoretical value. By using the appropriate sum rule for (d, p) stripping,[24,25] this finding implies a small reduction in the $p_{1/2}$ hole strength in the ^{14}N ground-state wave function. However, this requires a correspondingly large percent of increase in the weak $p_{3/2}$ hole strength, sufficient to bring them both into agreement with the strengths derived from the spectroscopic factor observed for the 6.32-MeV level in the present experiment. Better agreement with the stripping data is shown also in the strengths calculated from the ^{14}N ground-state wave functions derived from ^{14}C β decay.[26,27] These results are summarized in Table III.

TABLE III. Spectroscopic factors and neutron hole strengths in ^{14}N g.s.

	$^{14}N(d, p)^{15}N$ Present expt.	Shiffer *et al.*[a]	IPM[b]	From ^{14}C β decay Expt.[c]	Theoret.[d]
$S(1/2)$	1.31 ± 0.04	1.22 ± 0.18[e]	1.459	1.26	1.39
$u_{1/2}^2$	0.87 ± 0.03	0.81 ± 0.12	0.972	0.84	0.93
$S(3/2)$	0.10 ± 0.02[e]	0.14 ± 0.09	0.021	0.12	0.05
$u_{3/2}^2$	0.13 ± 0.03	0.19 ± 0.12	0.028	0.16	0.07

[a] Reference 24.
[b] Reference 23.
[c] Reference 26.
[d] Reference 27.
[e] Observed value: assuming that the ^{15}N g.s. is pure $(p_{1/2})^{-1}$, that the ^{15}N, 6.32-MeV level is pure $(p_{3/2})^{-1}$, and that the ^{14}N g.s. is of the form $a_{1/2}(p_{1/2})^{-2}+a_{1/2,3/2}(p_{1/2}, p_{3/2})^{-1}+a_{3/2}(p_{3/2})^{-2}$, then the ^{15}N spectroscopic factors $S(j)$ and the ^{14}N g.s. hole strengths u_j^2 are related by sum rules (Ref. 25), giving

$$\tfrac{1}{3}(2j+1)S(j)=a_j^2+\tfrac{1}{2}(a_{1/2,3/2})^2=u_j^2,$$

$$u_{1/2}^2+u_{3/2}^2=1, \qquad S(\tfrac{1}{2})+2S(\tfrac{3}{2})=1.5.$$

[23] S. Cohen and D. Kurath, Nucl. Phys. **A101**, 1 (1967).
[24] J. P. Schiffer, G. C. Morrison, R. H. Siemssen, and B. Zeidman, Phys. Rev. **164**, 1274 (1967).
[25] M. H. Macfarlane and J. B. French, Rev. Mod. Phys. **32**, 567 (1960).
[26] R. Sherr, J. B. Gerhart, H. Horie, and W. F. Hornyak, Phys. Rev. **100**, 945 (1955).
[27] W. M. Visscher and R. A. Ferrell, Phys. Rev. **99**, 649 (1955).

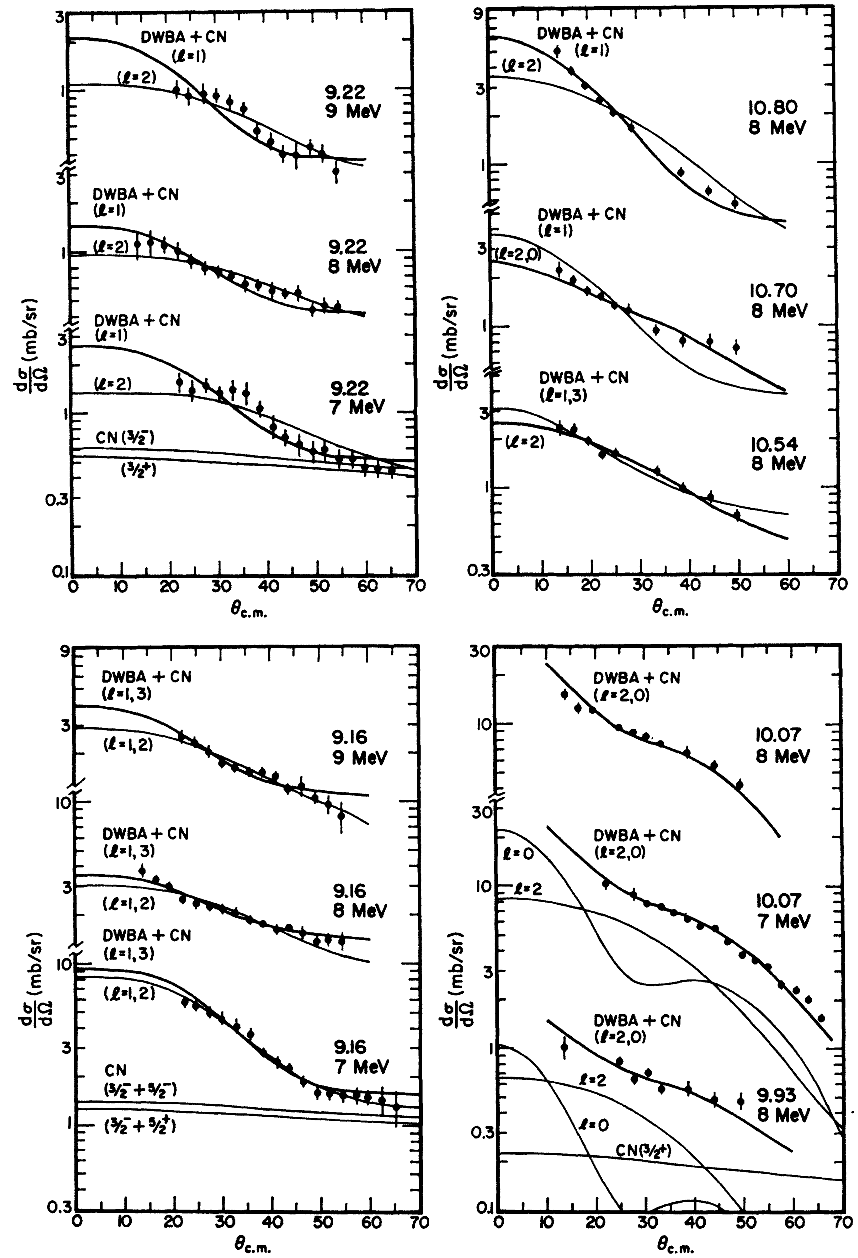

FIG. 4. $^{14}N(d, p)^{15}N$ angular distributions measured for levels from 9.16 to 10.80 MeV in ^{15}N. In some cases the fits for each of two possible l values, or combinations of l values, are compared. For further explanation see the caption to Fig. 3.

C. 7.15- to 8.57-MeV Levels

Spectroscopic factors near the single-particle prediction of 1.0 were obtained for four of these levels, from 7.15 to 8.31 MeV. In contrast to the 5.27-, 5.30-MeV doublet, these values are significantly *larger* than the IPM predictions (Table II). However, the result for the $\frac{3}{2}^+$, 8.57-MeV level is anomalously small. This level requires contributions from both $l=2$ and $l=0$ in order to satisfactorily fit the data (Fig. 3). Correspondingly, the fit to the predominantly $l=0$, $\frac{3}{2}^+$ level at 7.30 MeV is significantly improved by the inclusion of a small $l=2$ term; however, the $\frac{1}{2}^+$, 8.31-MeV level appears to be pure $l=0$. The fits at 9-MeV incident energy for these levels could probably be improved by an increase in the real potential-well depth from the value determined at 8 MeV. This was not done, in order to pressure relative consistency in the spectroscopic factors. The $l=2$ fits to the $\frac{5}{2}^+$, 7.15-MeV level and the $\frac{7}{2}^+$, 7.56-MeV level fall off more rapidly at backward angles than do the data points, a persistent feature of the DWBA in the trial calculations. Because of this, the spectroscopic factors for these levels were determined at the broad maxima rather than by the least-squares fitting procedure to the complete angular distribution, which was used for the other levels.

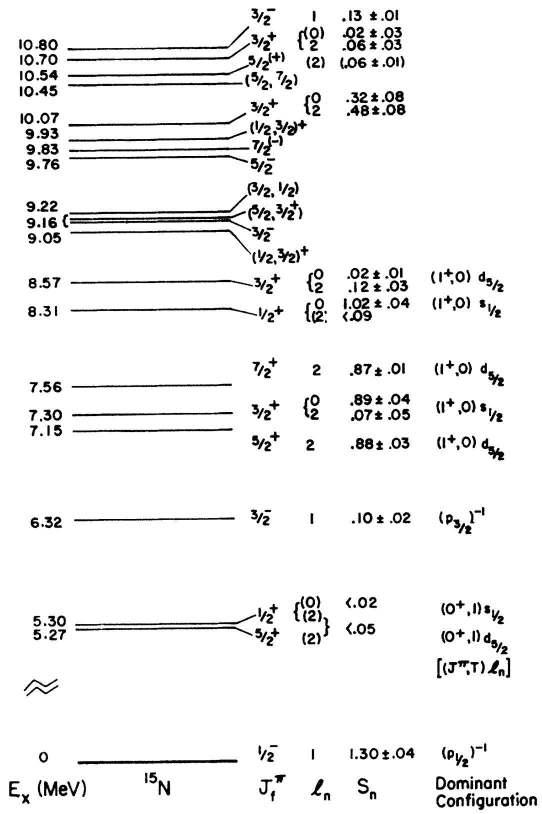

FIG. 5. Energy-level diagram of the neutron-bound states of ^{15}N, incorporating the results of the present and previous experiments (see text). From left to right are given the experimental excitation energies E_x, the spin-parity J_f^π (uncertain values enclosed in parentheses), the observed angular momentum transfer l_n for (d, p) stripping, the corresponding spectroscopic factor S_n, and the dominant single-particle configuration (see text).

D. 9.05- to 9.22-MeV Levels

The levels above 9 MeV divide into three multiplets of four close-lying levels each. The first quadruplet contains the 9.16-MeV degeneracy as well as levels at 9.22 and 9.05 MeV. The latter, previously determined[8] to be $\frac{1}{2}^+$ or $\frac{3}{2}^+$, was never completely resolved from the C^{12}-p_1 group, but indications at forward angles were that the cross section was relatively weak. The 9.16-MeV doublet and the 9.22-MeV level were also incompletely resolved from each other and at backward angles from the C^{12}-p_1 group, thus limiting the accuracy of the cross sections obtained for these levels. The predominantly ground-state decaying member of the 9.16-MeV doublet (9.16 A) is known[1,2] to be $\frac{3}{2}^-$. Correlation studies suggested[7] a spin of $\frac{3}{2}$ for the predominantly cascade-decaying level[28] (9.16 B). The present angular distributions can be fit by either a combination of $l=1$ and 2, implying $\frac{3}{2}^+$ or $\frac{5}{2}^+$ for 9.16 B, or a combination of $l=1$ and 3, implying $\frac{5}{2}^-$ or $\frac{7}{2}^-$. Since the latter combination gives a better fit to the forward-angle data at 8-MeV incident energy, it is preferred. The γ-ray branching ratio information[7] favors spin $\frac{5}{2}$. A $\frac{7}{2}^-$ assignment is unlikely because of the 7–9% branch to the $\frac{3}{2}^+$, 7.30-MeV level. No M2 or higher multipolarity branches have been observed in ^{15}N, and the observed lifetime limits[2] make such a transition improbable. On the other hand, a spin of $\frac{3}{2}^+$ would require a special explanation for the weakness of the ground-state transition, which could then go by E1.

The 9.22-MeV level is quite weak. Within the large uncertainties in the data, the angular distribution can be fit about equally well by $l=1$ or $l=2$; however, the $l=2$ fits can be criticized, since the data points at backward angles generally fall below the fitted curves for $l=2$, in contrast to the observed trend for the strong $l=2$ levels at 7.15 and 7.56 MeV. Both l values are consistent with the previously determined[1] spin of $\frac{3}{2}$ (90% probability) or $\frac{1}{2}$ (10% probability). Although the present experiment failed to determine definitely the l values for both the 9.16-MeV degeneracy and the 9.22-MeV level, it can be seen that the DWBA cross sections are sufficiently distinct that a high-resolution magnetic-spectrometer measurement of the angular distributions should be able to distinguish between the possibilities.

The 9.16 A level has been identified by Shukla[29] with the upper $\frac{3}{2}^-$ level obtained in a calculation based on the deformed model for ^{16}O of Brown and Green.[30] From the energy of 9.16 A, the model predicts an energy for the upper $\frac{1}{2}^-$ level of between 8.0 and 8.5 MeV. The energy of the 9.22-MeV level is not far from this prediction, and it is the only likely $\frac{1}{2}^-$ state below 11 MeV in ^{15}N. The largely collective nature of these states would also explain the small stripping amplitude for both the (d, p) and (d, n) reactions (Fig. 2).

E. 9.76- to 10.07-MeV Levels

The levels at 9.76 and 9.83 MeV were obscured in the present experiment by the C^{12}-$p_{2,3}$ groups. The 9.93-MeV level was relatively weak, and the cross section can be accounted for mainly by the compound nucleus contribution, with the addition of a small $l=2$, and possibly also an $l=0$, direct term. The strong $\frac{3}{2}^+$ level at 10.07 MeV is well fitted by a combination of $l=2$ and $l=0$ contributions.

F. 10.45- to 10.80-MeV Levels

The very weak 10.45-MeV cross section can be completely accounted for by the compound-nucleus term. The angular distribution for the 10.54-MeV, $J=\frac{5}{2}$ level is best fitted by $l=2$, implying positive parity, although a combination of $l=1$ and $l=3$ cannot be completely ruled out. A study of proton-capture γ rays tentatively assigned spin $\frac{3}{2}$ and negative parity to both

[28] During preparation of this paper a spin of $\frac{5}{2}$ has been reported for 9.16B by H. E. Siefken, P. M. Cockburn, and R. W. Krone, Bull. Am. Phys. Soc. **13**, 1423 (1968).

[29] A. P. Shukla, Ph.D. thesis, Princeton University Technical Report No. PUC-937-262, 1967 (unpublished).

[30] G. E. Brown and A. M. Green, Nucl. Phys. **75**, 401 (1966).

the 10.70- and 10.80-MeV levels.[31] Hebbard and Dunbar[32] have since observed an $l=2$ resonance shape for the 10.70-MeV level in proton elastic scattering, which implies positive parity for this level and thereby casts doubt on the negative-parity assignment for the 10.80-MeV level as well. In the present experiment, the angular distribution for the 10.70-MeV level is best fitted by $l=2$ with possibily some $l=0$ contribution, confirming the $\frac{3}{2}^+$ assignment. However, the 10.80-MeV angular distribution can be fitted satisfactorily only by $l=1$. The next-best fit, given by the $l=2$ cross section, clearly is unsatisfacotry at forward angles and is not improved by the addition of an $l=0$ term. This result unambiguously implies a $\frac{3}{2}^-$ assignment for the 10.80-MeV level. Figure 5 shows the levels of ^{15}N and summarizes the nuclear-structure information obtained from this and previous experiments.

V. WEAK-COUPLING MODEL FOR POSITIVE-PARITY STATES OF ^{15}N

The results of the present experiment persuasively lead to a weak-coupling model for the low-lying states of positive parity. Table II compares the spectroscopic factors obtained from DWBA fits to the data with those predicted by the IPM calculations of Halbert and French and by a weak-coupling model assuming an $s_{1/2}$ or $d_{5/2}$ particle outside a 0^+, $T=1$ core for the 5.27-, 5.30-MeV doublet and a 1^+, $T=0$ core for the 7.15–8.57-MeV quintuplet. For such an extreme model, the predicted spectroscopic factors are 0 for the doublet and the single-particle value of 1 for the five upper levels. Yet, the experimental values are generally close to those extremes, significantly closer than to the intermediate values which result from considerable core-configuration mixing in the IPM. The one exception is the highest level, at 8.57 MeV, which doesn't agree well with either model, probably because of mixing with higher-order configurations.

The core purity of these states is strikingly illustrated by the contrast in Fig. 2 between the spectra for the (d, p) reaction on the 1^+, $T=0$ ^{14}N ground state and the (d, n) reaction[14] on the 0^+, $T=1$ ^{14}C ground state (of which the isobaric analog in ^{14}N is the first excited state at 2.31 MeV). In the (d, p) reaction, the 5.27-, 5.30-MeV doublet is quite weak, while the levels from 7.15 to 8.31 MeV are populated strongly. In the complementary (d, n) reaction, however, the doublet is very strong, and the other states are relatively weak. It is not unreasonable to expect the ground states of these targets to provide good cores, since the captured particle is in the s-d shell, and its interaction with the p-shell particles of the core should be weak. In addition, core excitation is not favored energetically since the next-lowest $T=0$ state in ^{14}N is at 3.95 MeV, and the next-lowest positive-parity $T=1$ level is not until 8.63 MeV.

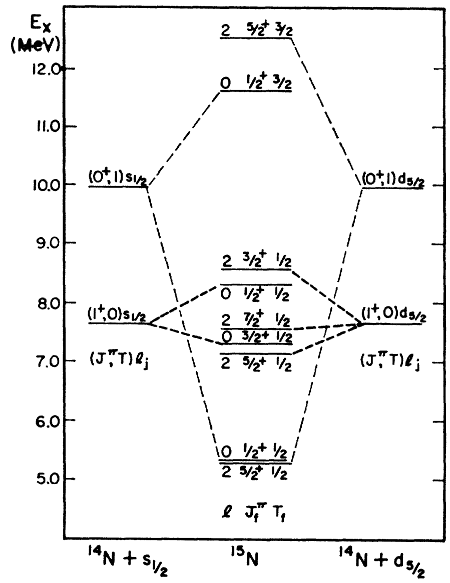

FIG. 6. Illustration of the weak-coupling model proposed in the text for the low-lying positive-parity levels of ^{15}N and the two known $T_f=\frac{3}{2}$ levels (center). On the left is shown the result of coupling an $s_{1/2}$ particle to a 1^+, 0 core (the ^{14}N ground state) which splits into $\frac{3}{2}^+$ and $\frac{1}{2}^+$ levels. The excitation energy of the degenerate (unsplit) state is taken to be 7.64 MeV, the center-of-mass energy, $\sum_J(2J+1)E_J/\sum_J(2J+1)$, of the experimental energies E_J. Above this by 2.31 MeV (the ^{14}N excitation energy) is the $s_{1/2}$ level built on a 0^+, 1 core corresponding to the ^{14}N first excited state and the ^{14}C ground state. This state is split by the $\mathbf{T}\cdot\mathbf{t}$ force into two $\frac{1}{2}^+$ levels with $T_f=\frac{1}{2}$ (5.30 MeV) and $T_f=\frac{3}{2}$ (11.62 MeV). On the right is shown the degenerate $d_{5/2}$ state coupled to a 1^+, 0 core which splits into 7^+, 5^+, and $\frac{3}{2}^+$ levels with a center-of-mass energy of 7.65 MeV. Again 2.31 MeV higher, the degenerate $d_{5/2}$ state coupled to a 0^+, 1 core is split by the $\mathbf{T}\cdot\mathbf{t}$ force into two 5^+ levels with $T_f=\frac{1}{2}$ (5.27 MeV) and $T_f=\frac{3}{2}$ (12.54 MeV).

The low-lying position of the 5.27-, 5.30-MeV doublet has yet to be explained, since in the weak-coupling model these states are built on a core, which in ^{14}N lies 2.31 MeV *above* the core for the upper positive-parity levels. The depression of the doublet, however, follows naturally from the inclusion of the $\mathbf{T}\cdot\mathbf{t}$ force,[6] which splits the levels built on the $T=1$ core into two levels each, the lower ones with $T_f=\frac{1}{2}$ (the 5.3-MeV doublet) and the upper ones with $T_f=\frac{3}{2}$ (the $\frac{1}{2}^+$ level at 11.62 MeV [31] and the $\frac{5}{2}^+$ level at 12.54 MeV[33]—isobaric analogs, respectively, of the ground state and first excited states of ^{15}C). This is illustrated in Fig. 6.

The relative splitting expected from the $\mathbf{T}\cdot\mathbf{t}$ force can be calculated in perturbation theory by the formula

$$\mathbf{T}\cdot\mathbf{t}=\tfrac{1}{2}[T_f(T_f+1)-T(T+1)-t(t+1)],$$

giving $(\mathbf{T}\cdot\mathbf{t})_{1/2}/(\mathbf{T}\cdot\mathbf{t})_{3/2}=(-1)/\frac{1}{2}=-2$ apart from differences in the matrix elements due to radial or energy dependence. The experimental values are -1.82 for the

[31] G. A. Bartholemew, F. Brown, H. E. Gove, A. E. Litherland, and E. F. Paul, Can. J. Phys. **33**, 441 (1955).
[32] D. F. Hebbard and D. N. F. Dunbar, Phys. Rev. **115**, 624 (1958).
[33] J. D. Henderson, E. L. Hudspeth, and W. R. Smith, Phys. Rev. **172**, 1058 (1968).

$\frac{5}{2}^+$ levels and -2.78 for the $\frac{1}{2}^+$ levels. The strength factor, usually written v_1/A, is large in this case because of the relatively small mass A. The total splitting is $\frac{3}{2}v_1/A$, giving $v_1 \approx 73$ and 63 MeV for the $\frac{5}{2}^+$ and $\frac{1}{2}^+$ levels, respectively. This is somewhat lower than the value $v_1 \approx 100$ MeV usually associated with heavier nuclei,[34] but compares with the value $v_1 \approx 50$ MeV derived[6] from the calculation by Elliott and Flowers[35] for ^{16}O.

The question of the experimental disagreement with the IPM remains. The Halbert and French calculations can be criticized for the exchange mixture used in the two-body interaction potential of the form,

$$H_{\text{int}} = \sum_{i<j} (a\boldsymbol{\sigma}_i \cdot \boldsymbol{\sigma}_j + b)(\boldsymbol{\tau}_i \cdot \boldsymbol{\tau}_j) V(r),$$

with $a = 8.5$ MeV, $b = 3.7$ MeV, and a $V(r)$ of Yukawa shape with $r_0 = 1.385$ F. The $\mathbf{T} \cdot \mathbf{t}$ force is related to the second term, while the first term is responsible for the mixing between the 0^+, $T=1$ and 1^+, $T=0$ states. Results of quasielastic scattering studies in light nuclei, including ^{15}N, indicate a ratio of $a/b \simeq 0.9$–1.[36] Recent DWBA calculations for ^{14}C$(p, n)^{14}$N to the 2.31-MeV level give a value of $b = 9$ MeV, and to the 1^+, $T=0$ level at 3.95 MeV, a value of $a = 7$ MeV.[37] Thus, the first term in H_{int} is of approximately the right strength in the IPM calculations, but the second term is too small by factor of 2. An increase in this strength would increase the $\mathbf{T} \cdot \mathbf{t}$ splitting, thus lowering the unmixed $T=1$, $T_f = \frac{1}{2}$ levels. This must reduce the mixing, since it increases the energy denominator in a perturbation expansion for the wave functions, even though the numerator, which is proportional to the first term, is relatively unchanged. The effect would be to bring the IPM into closer agreement with experiment and with the weak-coupling model.

In summary, it is reasonable to expect a weak-coupling model to give a good approximation to the low-lying positive-parity states of ^{15}N, since the outside particle is in the next shell, and since the p-shell particles of the core are tightly bound. In addition, the large $\mathbf{T} \cdot \mathbf{t}$ force, due to the light mass, depresses the unperturbed $T_f = \frac{1}{2}$ levels built on a $T=1$ core sufficiently below those built on a $T=0$ core to effectively reduce configuration mixing. This model has the virtue of simplicity, which makes comparison with experiment straightforward. Of course, because of this simplicity, the model should not be taken too literally in detailed comparison to the complex system which is the nucleus even for mass 15. Nevertheless, as seen here, the agreement to first order is surprisingly good. It should be pointed out that the validity of the ^{14}N states as a core is due to the validity of the ^{16}O closed shell. In a sense, the weak-coupling model discussed here is equivalent to considering one-particle–two-hole states in a ^{16}O core. Because this is a relatively good closed shell, the interaction of the outside particle with the holes should be weak. ^{14}N then gives us a good picture of how the two-hole states in the core will look.

Note added in proof: ^{14}N$(^3$He$, d)^{15}$O relative spectroscopic factors for levels in ^{15}O analogous to some of the levels observed by us in ^{15}N have been presented in an article by Alford and Purser,[38] in which comparison was made to spectroscopic factors taken from this manuscript prior to publication. It must be pointed out, as Ref. 38 neglects to do so, that we have obtained absolute spectroscopic factors which thus require no normalization. Normalizing their results to the ground state, Alford and Purser get good relative agreement with the spectroscopic factor predicted by the IPM calculation of Halbert and French.[5] However, previous ^{14}N$(d, p)^{15}$N stripping studies also have appeared to be in good relative agreement with the IPM predictions.[5,25] It was only when absolute spectroscopic factors were extracted from our data, taking into account the importance of compound nuclear contributions to the weaker cross sections, that the disagreement with the IPM became evident. It is clear that absolute cross-section measurements are necessary for a decisive comparison between experimental and theoretical spectroscopic factors.

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[34] J. M. Soper, in *Isobaric Spin in Nuclear Physics*, edited by J. D. Fox and D. Robson (Academic Press Inc., New York, 1966), p. 565.

[35] J. D. Elliott and B. H. Flowers, Proc. Roy. Soc. (London) **242**, 57 (1957).

[36] J. D. Anderson, Ref. 34, p. 530.

[37] C. Wong, J. D. Anderson, J. McClure, B. Pohl, V. A. Madsen, and F. Schmittroth, Phys. Rev. **160**, 769 (1967).

[38] W. P. Alford and K. H. Purser, Nucl. Phys. **A132**, 86 (1969).