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Structure of ^{17}C and ^{17}N

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The energy spectra and wave functions of ^{17}C and ^{17}N are calculated using a modification of the Millener-Kurath interaction. The results are used to predict the half-life and decay modes of both the allowed and first-forbidden β^- decays of ^{17}C as well as $^{18}O(d,{}^3He)^{17}N$ spectroscopic factors and electromagnetic transition rates in ^{17}N.

I. INTRODUCTION

This study of $^{17}C(\beta^-)^{17}N$ and the structure of ^{17}C and ^{17}N is part of an ongoing investigation into the information obtainable from the β^- decay of neutron-rich nuclei in the $A\sim16$ and 40 regions. For very neutron-rich nuclei, β^- decay is usually the most important source of nuclear structure information, and sometimes the only source. Previous studies were made of nuclei near $A=40$ with $N>20$,[1-6] and of $^{19}N(\beta^-)^{19}O$.[7] Most of these studies, including the ^{19}N decay, utilized the β^--delayed γ-ray results of Dufour *et al.*[8] The present study of ^{17}C decay also relies on these results.

II. THE CALCULATION

A. Introduction

The decay of ^{17}C is typical of those neutron-rich nuclei in which the valence neutrons occupy a different major shell from the valence protons. As in other such cases, it is expected to proceed via first-forbidden transitions to the lowest configuration of the daughter nucleus and by Gamow-Teller (GT) transitions to the non-normal parity $1\hbar\omega$ excitations of these states. The shell-model calculations for these configurations are performed with cross-shell interactions developed specifically to describe levels with valence nucleons active in several major shells simultaneously. For the nuclei near $A=16$, a modification of the Millener-Kurath interaction[9] (designated MK3) is used. Another derivative of the MK interaction has been used[4-6] for the cross-shell matrix elements near $A=40$. The calculations are carried out using the shell-model code OXBASH,[10] and the techniques have been fully described in the previous studies.[1-7]

B. The interaction

The lowest energy configurations for many of the neutron-rich light nuclei with $Z<8$ and $N>9$ consist of p-shell proton holes interacting with sd-shell neutrons. Empirical interactions, fitted to large bodies of energy-level data, are available for the interactions within the major shells. We use the Cohen-Kurath (8–16) 2BME interaction[11] for the p shell and the Chung-Wildenthal interaction[12] for the sd shell. For nuclei of the type described above, such as ^{17}C, only the $\pi p^{-1}\nu(sd)$ interaction, or equivalently the $T=1$ particle-hole interaction, is required, although the $T=0$ particle-hole interaction does play a role in the structure of the daughter nucleus. The most important interactions are between $0p_{1/2}$ holes and $0d_{5/2}$ or $1s_{1/2}$ particles. The most direct information on these interactions comes from the low-lying quartet of levels in ^{16}N which have dominant $p_{1/2}^{-1}d_{5/2}$ and $p_{1/2}^{-1}s_{1/2}$ configurations. It is evident that the $p_{1/2}^{-1}s_{1/2}$ $T=1$ matrix elements are less repulsive than the $p_{1/2}^{-1}d_{5/2}$ $T=1$ matrix elements. Thus, in ^{15}C, with two proton holes, the $1/2^+$ level falls below the $5/2^+$ level. The original MK interaction,[9] which consisted of central, tensor, and spin-orbit components with a single term of Yukawa radial form in each spin-isospin channel of the particle-particle force, was chosen to reproduce this behavior and to give a reasonable fit to other features of simple particle-hole spectra. However, as noted by Barker,[13] the MK interaction fails to give the correct ordering of the $p_{1/2}^{-1}d_{5/2}$ $2^-,3^-$ doublet. This failing has immediate consequences for the spectra of ^{17}N and ^{18}N obtained essentially by the addition of $d_{5/2}$ neutrons. For example, the ordering of $3/2^-,5/2^-$ and $7/2^-,9/2^-$ doublets in ^{17}N is inverted.[13,14] Barker showed,[13] using a simple $p_{1/2}^{-1}d_{5/2}^n$ model, that by adjusting the basic $p_{1/2}^{-1}d_{5/2}$ (and $p_{1/2}^{-1}s_{1/2}$) matrix elements to fit the ^{16}N spectrum exactly, much improved spectra could be obtained for ^{17}N and ^{18}N. Very similar results are obtained from full $1\hbar\omega$ shell-model calculations when the same basic matrix elements are adjusted to fit ^{16}N.[14]

When the MK interaction was constructed, it was known that it is impossible to obtain the correct ordering of the $2^-,3^-$ doublet in ^{16}N with a single-range force except in the limit of very short range. The interaction, designated MK3, that is used in this paper is based on a multirange parametrization, obtained by Hosaka *et al.*,[15] of a G matrix based on the Paris potential.[16] Adjustments were made to the strengths of a number of components in the G matrix to obtain an improved fit to the particle-hole spectrum of mass 16. In particular, the spacings of the ^{16}N levels discussed above are reproduced to within 60 keV at worst. The improvement is obtained with increased configuration mixing; the 2^- and 3^- levels are about 92% $p_{1/2}^{-1}d_{5/2}$ for the MK3 interaction compared with about 96% for the original MK interaction.

The MK3 interaction, which is tested here for ^{17}C and ^{17}N, should be regarded as an interim step towards a particle-hole interaction which is optimized by fitting a wide range of data in the ^{16}O region with multiparticle, multihole configurations, which play an important role in the spectra of low-isospin states, included. Since the interaction is given in the form of a potential, it can be used to calculate all cross-shell matrix elements, including those which involve the $0s$ and $0f\,1p$ orbits.

C. The calculation

For $A=17$, we define the $(0s)^4(0p)^{12}(1s,0d)$ configuration as $0\hbar\omega$. The low-lying ^{17}N negative-parity levels arise predominantly from the $1\hbar\omega$ $(0s)^4(op)^{11}(1s,0d)^2$ configuration. In order to avoid incomplete separation of spurious states and also to obtain meaningful $E1$ rates, the model space for the even-parity states of ^{17}N must include all possible $2\hbar\omega$ excitations of the $1\hbar\omega$ model space. This requirement results in $(0s)^4(0p)^{11}(1s,0d)^1(0f,1p)^1$ and $(0s)^3(0p)^{12}(1s,0d)^2$ components as well as the main $(0s)^4(0p)^{10}(1s,0d)^3$ ones. It is found that the $(0f,1p)$ admixtures are of order 1% but have a considerable effect on $E1$ rates. For ^{17}C, with $T=5/2$, $p^{-2}(sd)^3$ configurations are the only allowed components for the lowest oscillator energy and, as such, are free from spurious center of mass motion.

Gamow-Teller transitions are calculated using the "free nucleon" operators. Quenching of GT rates is known to be largely state independent and is $\sim$40% in this mass region.[17] We allow for this quenching by scaling the calculated GT rates by 0.6.

The appropriate first-forbidden operators depend on the model space used, the radial wave functions of the valence nucleons, and other factors. The effective operators used are similar to those for the $A=40$ region described in Refs. 5 and 6. We use harmonic oscillator (HO) wave functions with a length parameter b of 1.763 fm and make a crude correction[6] for the use of HO wave functions rather than more realistic ones [the timelike (spacelike) rank-zero matrix elements are decreased (increased) by 10%]. The enhancement of the timelike component of the rank-zero axial current by pion-exchange currents is taken to be 64%. This value is close to that estimated theoretically[18] for the ratio of two-body to one-body contributions to the shell-model matrix elements. As reviewed by Adelberger and Haxton,[18] the exchange current basically renormalizes the one-body axial charge, and the ratio of matrix elements is largely insensitive to the particular choice of shell-model wave functions. We previously used enhancement factors of 40% and 64% in surveys of $J^{\pm}\rightarrow J^{\mp}$ first-forbidden beta decays in the $A=16$ region[19] and the $A=40$ region.[6] Finally, to compensate for the omission of 2p-2h correlations, a quenching of 0.7 is used for the rank-two matrix element. This value is consistent with our overestimate by a factor of 2 for the rates of the unique first-forbidden ground-state decays of ^{16}N and ^{17}N in $1\hbar\omega\rightarrow 0\hbar\omega$ calculations.

Electromagnetic transition rates are calculated with HO radial wave functions. For $E1$ and $M2$ transitions, the free nucleon operators are used; $E2$ transitions are calculated with $e_p=1.35e$, $e_n=0.35e$; and $E3$ transitions with $e_p=1.5e$, $e_n=0.5e$. $M1$ transitions use the effective operators obtained via least-square fits to $M1$ rates in $(1s,0d)$ nuclei.[20] Their use in ^{17}N is justified because the quenching of $M1$ transitions is relatively shell independent, and because $M1$ transitions in ^{17}N are dominated by transitions within the $(1s,0d)$ shell.

III. RESULTS

A. The ^{17}C energy spectrum and wave functions

We expect the lowest configurations in ^{17}C to arise from the coupling of two proton holes to the lowest $(1s,0d)^3$ states for three neutrons. In the terminology of the weak-coupling model, these states are of the form ^{14}C$(0^+$;g.s.$)\otimes{}^{19}$O(J^{π}), where the ^{19}O states of interest are the $5/2^+$ ground state, the $3/2^+$ state at 96 keV, and the $1/2^+$ state at 1472 keV. The spectrum of ^{18}N states of the form ^{15}N$(1/2^-$;g.s.$)\otimes{}^{19}$O(J^{π}) gives important guidance as to what should be expected for the low-lying spectrum of ^{17}C. The experimental spectrum of low-lying ^{18}N states is shown in Fig. 1(a) along with the parent nucleus ^{19}O. The ground state of ^{18}N is known, from the β^- decay of ^{18}N,[25] to have $J^{\pi}=1^-$, and thus has the dominant configuration ^{15}N$(1/2^-$;g.s.$)\otimes{}^{19}$O$(3/2^+)$. Two states at 120 keV and 747 keV are excited in the ^{18}O(^{7}Li,^{7}Be)^{18}N charge-exchange reaction.[23] Since the ^{19}O $(5/2^+)$ level has a substantial $d_{5/2}$ parentage to the

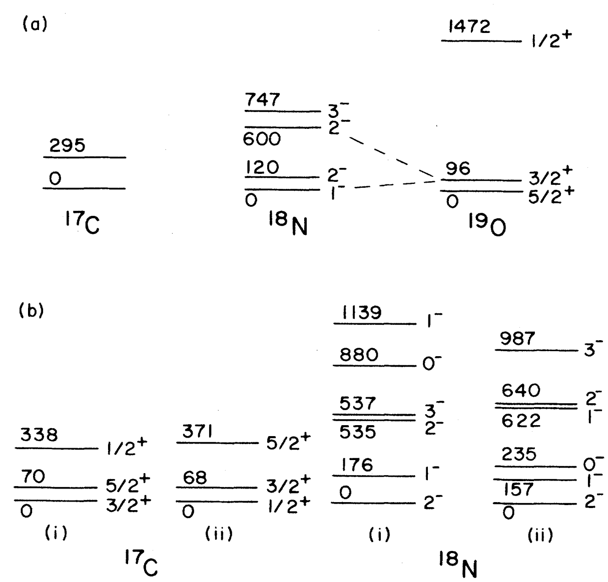

FIG. 1. (a) Energy level spectra for ^{17}C (Refs. 21 and 22), ^{18}N (Refs. 23 and 24), and ^{19}O (Ref. 24). The ^{18}N configurations thought to be of the form $p_{1/2}^{-1}\otimes{}^{19}O(3/2^+)$ are indicated by dotted lines. (b) Shell-model spectra for ^{17}C and ^{18}N calculated using (i) a modified MK interaction (Ref. 14) and (ii) the MK3 interaction (Sec. II B).

^{18}O g.s.,[26] a necessary condition for a large $p_{1/2} \rightarrow d_{5/2}$ one-body density-matrix element for excitation in inelastic scattering or charge-exchange reactions, it is natural to interpret these two levels as 2^- and 3^- states with dominant ^{15}N($1/2^-$)$\otimes$^{19}O($5/2^+$) components in their wave functions. This interpretation[26] is consistent with the strong $M2$ excitation[27] in ^{18}O of the apparent analog of the ^{18}N 120 keV level at 16.40 MeV in ^{18}O by inelastic electron scattering and with the excitation[28] of the 17.02 MeV level (the probable analog of the ^{18}N 3_1^- state) at higher momentum transfer in the same reaction. Finally, a level at 580–600 keV is excited in ^{18}O(^{7}Li,^{7}Be)^{18}N reaction[23] and in the ^{14}C(^{7}Li,^{3}He)^{18}N reaction.[29] With the interpretation of this latter level as 2^-, the centroid of the ^{15}N($1/2^-$)$\otimes$^{19}O($3/2^+$) doublet lies 110 keV below the ^{15}N($1/2^-$)$\otimes$^{19}O($5/2^+$) doublet in ^{18}N. This leads us to expect that the ^{14}C(0^+)$\otimes$^{19}O($3/2^+$) configuration lies below the ^{14}C(0^+)$\otimes$^{19}O($5/2^+$) configuration in ^{17}C.

Two peaks attributed to the production of ^{17}C and separated by 295 keV are observed in the ^{48}Ca(^{18}O,^{17}C)^{49}Ti reaction.[21] The upper peak is much more strongly excited, and we identify it with the $5/2^+$ state which should be most strongly populated in any two-step direct-reaction process. Therefore, based on the systematics described above, it is unlikely that ^{17}C has a $5/2^+$ ground state. Our analysis of the γ-ray spectra following the β^- decay of ^{17}C, described later, also rules against $5/2^+$ as the ground-state spin.

The remaining possibility for the ground-state spin of ^{17}C is $1/2^+$. The dominant components in the Chung-Wildenthal wave functions[12] for ^{19}O are 79% $(d_{5/2}^3)_{5/2^+}$, 66% $(d_{5/2}^3)_{3/2^+}$, and 90% $(d_{5/2}^2 s_{1/2})_{1/2^+}$. Certainly, as described in Sec. II B, we expect the particle-hole interaction to lower the ^{14}C(0^+)$\otimes$^{19}O($1/2^+$) configuration relative to the ^{14}C(0^+)$\otimes$^{19}O($5/2^+$,$3/2^+$) configurations. There is little experimental evidence for the ^{15}N($1/2^-$)$\otimes$^{19}O($1/2^+$) states in ^{18}N, although there is some evidence for states near 1 MeV excitation energy in heavy-ion charge-exchange reactions.[23,30] Shell-model predictions for the low-lying states of ^{17}C and ^{18}N are given in Fig. 1(b). We note that the Chung-Wildenthal interaction[12] reproduces the energies of the ^{19}O states, not shown in Fig. 1(b), rather accurately. However, the fact that $E_x(3/2^+)-E_x(5/2^+)=206$ keV is 110 keV too large must be taken into account given the small energy splittings of configurations obtained by coupling $p_{1/2}$ holes to the ^{19}O configurations. Spectra are given for two particle-hole interactions. In case (i), the diagonal $p_{1/2}^{-1}s_{1/2}$ and $p_{1/2}^{-1}d_{5/2}$ matrix elements of the original MK interaction have been adjusted to achieve a perfect fit to the energies of the low-lying quartet of states in ^{16}N. Case (ii) corresponds to the MK3 interaction described in Sec. II B. In both cases, $3/2^+$ comes below $5/2^+$ in ^{17}C, consistent with the empirical deductions above. A 26% $(d_{5/2}^2 s_{1/2})$ component in the ^{19}O ($3/2^+$) model wave function, reflecting a parentage to ^{18}O (2^+), together with the aforementioned properties of the particle-hole interaction, are responsible for this behavior. The major difference between cases (i) and (ii) is that the ^{17}C and ^{18}N states based on ^{19}O ($1/2^+$) come lower with the MK3 interaction, despite the fact that the two particle-hole interactions are chosen to give similar results for ^{16}N. For the MK3 interaction, the $1/2^+$ and $3/2^+$ states are predicted to be essentially degenerate, the more so when allowances are made for the small discrepancies between theory and experiment for the ^{19}O spectrum. Thus, the present shell-model calculations cannot give a definitive prediction for the ground-state spin of ^{17}C, and $1/2^+$ and $3/2^+$ both remain viable possibilities.

B. The ^{17}N energy spectrum and wave functions

1. The energy spectrum

The MK3 2p-1h and 3p-2h energy spectra are compared to experiment in Fig. 2. Both the odd- and even-parity model spectra are shifted in energy relative to experiment so that the rms deviation of the excitation energies, ΔE_x(rms), for the indicated correspondence (dashed lines) is a minimum for each. These shifts are made because no attempt was made to obtain accurate absolute binding energies for the two spectra. The values of ΔE_x(rms) for the two model spaces are 468 keV for 2p-1h and 290 keV for 3p-2h. There is seen to be a good one-to-one correspondence between experiment and theory. All known ^{17}N levels up to 6 MeV excitation are accounted for. Only one model state below 5.5 MeV excitation has no experimental counterpart. This is the $7/2_2^-$ shown at 4.97 MeV.

An orientation towards the ^{17}N odd-parity spectrum is given by consideration of the weak coupling of a $p_{1/2}$ proton hole to $(1s,0d)^2$ states of ^{18}O. Thus, the first ten odd-parity states on the left-hand side of Fig. 2 are mainly composed of

$$(\pi p_{1/2})^{-1}\otimes[^{18}\mathrm{O}(0_1^+,2_1^+,4_1^+,2_2^+,0_3^+,3_1^+)] \ .$$

Since ^{18}O has rather low-lying intruder states, e.g., the the 4p-2h 0_2^+ state at 3.63 MeV, it would appear at first that ^{17}N would also. However, the energetically favored $(1s,0d)$ clusters cannot couple to the energetically favored $(1p_{1/2})^{-3}$ clusters, but instead demand participation of the $p_{3/2}$ shell. For the odd-parity 4p-3h model space, we would expect

$$[^{13}\mathrm{C}(1/2^-)\otimes{}^{20}\mathrm{F}(2^+)]_{J^\pi=3/2^-,5/2^-}$$

to be lowest. To get an estimate for the excitation energies of such states, we use the Reehal-Wildenthal interaction[31] in the full $(0p_{1/2},0d_{5/2},1s_{1/2})^5$ model space. Such calculations have a good track record for estimating the excitation energies of multiparticle, multihole excitations in the $A=16$ region. In this case, the lowest dominantly 4p-3h states are $5/2^-$ and $3/2^-$ states at excitation energies of 6.3 and 6.5 MeV. Alternatively, the weak-coupling model of Bansal and French[32] places the centroid of the $5/2^-$,$3/2^-$ doublet 6.3 MeV above the weak-coupled 2p-1h $1/2^-$ ground state when the parameters of Manley *et al.*[33] are used in $V_{ph}=a+b\mathbf{t}_p\cdot\mathbf{t}_h$. A slightly better estimate of 6.5 MeV is obtained by using the energies of known ^{13}C g.s.$\otimes^{20}$Ne$(J_1, T=0)$ states with $J=4$ or 6 in ^{17}O to eliminate the parameter a.

The 3p-2h spectrum can also be understood well in terms of weak-coupling configurations. ^{14}C$(0^+)\otimes^{19}$F$(1/2_1^+, 5/2_1^+, 3/2_1^+, 9/2_1^+)$ configurations dominate the lowest states with these spins, and ^{14}N$(1^+)\otimes^{19}$O$(5/2_1^+, 3/2_1^+)$ configurations account for large components of the remaining positive-parity states in Fig. 2.

2. *Spectroscopic factors in the ^{18}O$(d, ^3$He$)^{17}$N reaction*

Comparison of our predictions for the proton pickup spectroscopic factors C^2S to the experimental values from the ^{18}O$(d, ^3$He$)^{17}$N reaction is made in Table I. The experimental data are from Mairle *et al.*[34] as compiled by Ajzenberg-Selove.[22] The results for $l_p=1$ are in fair agreement with experiment. In particular, the $p_{1/2}$ pickup strength is concentrated in the ^{17}N ground state, and the largest piece of the $p_{3/2}$ pickup strength is contained in the 5514 keV level. As noted in the preceding section,

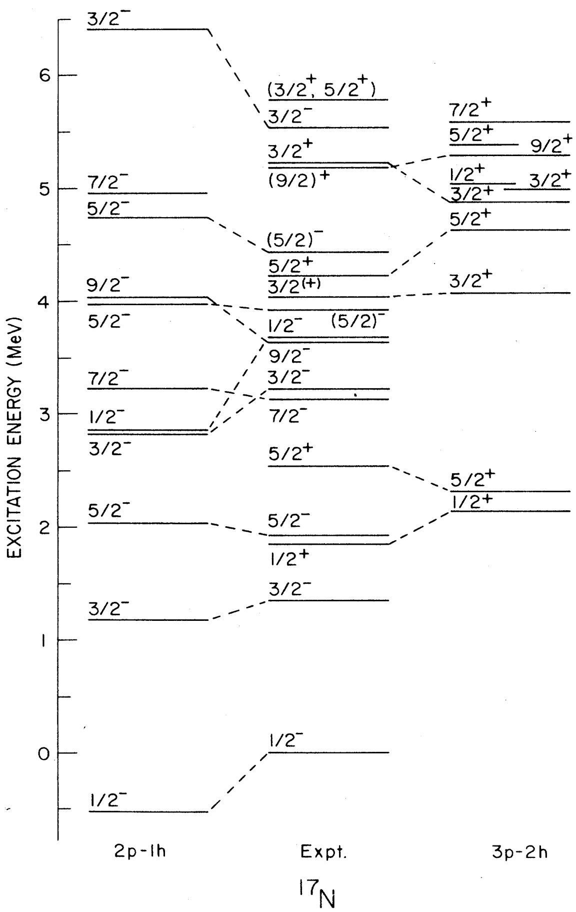

FIG. 2. Energy-level spectrum of ^{17}N. The experimental data are from Ref. 22 and from the Appendix. Uncertain assignments are enclosed in parentheses. The 2p-1h and 3p-2h model spectra are discussed in the text. The dashed lines indicate likely correspondences between theory and experiment.

TABLE I. Spectroscopic factors for ^{18}O$(d, ^3$He$)^{17}$N reactions (Ref. 34). The ^{18}O model space is $(1s, 0d)^2$.

State	E_x	l_p	Expt. C^2S	Model
$1/2^-$	0	1	2.02	1.76
$1/2^-$	3660	1		0.00
$3/2^-$	1374	1	0.38	0.69
$3/2^-$	3204	1	0.05	0.26
$3/2^-$	5514	1	1.83	2.20
$3/2^-$	6990	1	0.32	0.03
$1/2^+$	1850	0	0.41	
$5/2^+$	2526	2	0.53	

a $3/2^-$ state with the configuration ^{13}C g.s.$\otimes^{20}$F g.s. is expected between 6 and 7 MeV in excitation energy. To the extent that the dominant 4p-2h component in the ^{18}O ground state is of the form ^{14}C g.s.$\otimes^{20}$Ne g.s., the 4p-3h component in ^{17}N does not contribute to the $p_{3/2}$ pickup strength. However, mixing between the $p_{3/2}^{-1}\otimes^{18}$O g.s. and ^{13}C g.s.$\otimes^{20}$F g.s. configurations could account for the pickup strength observed for the 6990 keV level.

The experimental results[34] for the pickup of $1s_{1/2}$ and $0d_{5/2}$ protons ($C^2S=0.41\pm0.14$ and 0.53 ± 0.17 respectively), if taken at face value, indicate very large amplitudes of core excitation in the ^{18}O ground state and possibly also in the ^{17}N $1/2_1^+$ and $5/2_1^+$ states. To illustrate this point, the 0^+ states of $(0s)^4(0p)^{10}(1s,0d)^4$ were diagonalized with the MK3 interaction, and the proton pickup amplitudes for the 0_1^+ state of this space to the ^{17}N $1/2^+$ and $5/2^+$ states were calculated. It was found that almost all the strength was in the first $1/2^+$ and $5/2^+$ states with C^2S values of 0.49 and 1.10, respectively. These numbers are within 10% of a simple estimate obtained using the weak-coupling configurations ^{14}C g.s.$\otimes^{20}$Ne g.s. and ^{14}C g.s.$\otimes^{19}$F (J^π), in which case $C^2S(^{17}\mathrm{N})=\frac{1}{2}S(^{19}\mathrm{F})$. Thus, assuming 4p-2h admixtures in ^{18}O only, we would estimate $\sim$80% and 50% 4p-2h admixture in the ^{18}O ground state from the experimental results of Table I. However, this is not a fair comparison since, to the extent that the 4p-2h component in the ^{18}O ground state involves the promotion of $p_{1/2}$ protons to the *sd* shell, the C^2S values for $0p_{1/2}$, $1s_{1/2}$, and $0d_{5/2}$ pickup should sum to 2.0, while the experimental values in Table I sum to 2.96. Nevertheless, after renormalization, a 33% 4p-2h admixture is still required to give the experimental C^2S value for $0d_{5/2}$ pickup. This admixture is a factor of 2 more than that found by Hayes *et al.*[35] from an examination of $E2$ observables in ^{18}O. One remaining fact to consider is that the well-depth procedure, used by Mairle *et al.*[34] to extract spectroscopic factors, tends to overestimate spectroscopic factors when the separation energy is greater than the "natural" Hartree-Fock energies for the single-particle orbit.[36] We would identify the Hartree-Fock energy for a $d_{5/2}$ proton with the proton separation energy for ^{17}F which is 0.6 MeV, to be compared with the separation energy for the ^{17}N $5/2_1^+$ level of 18.5 MeV. Mairle *et al.*[34] have noted difficulties with the DWBA analysis for the analog $1/2^+$ and $5/2^+$ states of ^{17}O and have assigned large errors to the C^2S values for both ^{17}O and ^{17}N. On the other hand, the proton separation energy for the ^{17}N ground state of 15.94 MeV is quite close to the separation energy of a $p_{1/2}$ proton from ^{16}O, and the DWBA analysis is expected to be more reliable. We conclude that the size of the C^2S values for $1s_{1/2}$ and $0d_{5/2}$ proton pickup from ^{18}O may not be such a problem to understand as it appears to be at first sight. Certainly, a reanalysis of the ^{18}O$(d,{}^3\mathrm{He})^{17}$N pickup data using the theory of one-nucleon overlap functions described by Satchler[36] would be an interesting exercise.

A calculation by Reehal and Wildenthal[31] in the full $(0p_{1/2},1s_{1/2},0d_{5/2})^n$ space gives C^2S values of 1.15, 0.20, and 0.57 for pickup to the $1/2_1^-$, $1/2_1^+$, and $5/2_1^+$ levels of ^{17}N, respectively. In this calculation the ^{17}N $1/2_1^+$ and $5/2_1^+$ states are both 30% 5p-4h and the ^{18}O g.s. is 44% 2p-0h, 42% 4p-2h, and 14% 6p-4h, and the predicted ratio of C^2S values for $d_{5/2}$ to $p_{1/2}$ pickup is actually twice the experimental value. Although the predictions from highly truncated shell-model spaces, such as the Reehal-Wildenthal one, should be viewed with a high degree of skepticism, further study of core excitations in this region of A is suggested. Indeed, weak-coupling arguments suggest that the ^{12}C g.s.$\otimes^{21}$F g.s. configuration should appear at quite low excitation energy in ^{17}N so that an appreciable 5p-4h admixture is possible for the lowest positive-parity states in ^{17}N. However, we would expect the 4p-2h and 6p-4h components in the ^{18}O g.s. to be much smaller than that given by the Reehal-Wildenthal calculation. Nevertheless, the 6p-4h$\rightarrow$5p-4h amplitude could be significant compared with the 4p-2h$\rightarrow$3p-2h amplitude. The OXBASH code is not well suited to treat multiparticle, multihole configurations. Rather, weak-coupling or SU(3) codes, which allow meaningful truncations of the full $n\hbar\omega$ model spaces for the energetically favored multiparticle, multihole intruder states, should be used.

3. *Electromagnetic transitions in ^{17}N*

Predictions of the present calculation are compared to experiment in Table II, which includes data for the known bound yrast states. The data are from results reviewed by Ajzenberg-Selove[22] with spin-parity assignments as discussed in the Appendix.

We would say that the predictions of Table II are generally in satisfactory agreement with experiment. Except for the $9/2_1^-\rightarrow7/2_1^-$ transition, the four known $M1$ rates are reproduced within a factor of 2, as is the one known $M2$ rate. The predictions for the four known $E2$ rates are in excellent agreement with experiment, while the predicted $x(E2/M1)$ values are consistent with experiment (or nearly so). For the 4006 keV $3/2^+$ state, the experimental data consist of branching ratios of $\geq 85\%$ and $\leq 15\%$ to the $5/2^+$ 2156 keV level and the $1/2^+$ 1850 keV level, respectively. As can be seen, the predicted Γ_γ for these two branches is in agreement with these limits. Note that the $3/2_1^+\rightarrow5/2_1^+$ $M1$ transition strength is predicted to be unusually strong. This follows

TABLE II. Comparison of experimental and predicted electromagnetic decays of yrast states in ^{17}N.

E_{xi} (keV)	E_{xf} (keV)	J_i^π	J_f^π	Quantity[a]	Expt.[b]	Shell model[b]
1374	0	$3/2_1^-$	$1/2_1^-$	$B(M1)$	132(50)[−3]	207[−3]
				$x(E2/M1)$	0.00(3)	+0.044
1850	0	$1/2^+$	$1/2^-$	$B(E1)$	4.9(16)[−6]	960[−6]
	1374		$3/2^-$	$B(E1)$	45(19)[−6]	1070[−6]
1907	0	$5/2^-$	$1/2^-$	$B(E2)$	0.87(16)	1.27
	1374		$3/2^-$	$B(M1)$	4.5(9)[−3]	11[−3]
				$x(E2/M1)$	−0.05(14)	+0.015
2526	0	$5/2^+$	$1/2^-$	$B(M2)$	0.22(3)	0.42
				$x(E3/M2)$	−0.07(18)	−0.08
	1374		$3/2^-$	$B(E1)$	10(2)[−6]	2.7[−6]
	1850		$1/2^+$	$B(E2)$	8.1(13)	7.9
	1907		$5/2^-$	$B(E1)$	79(9)[−6]	55[−6]
3129	1907	$7/2^-$	$5/2^-$	$B(M1)$	63(19)[−3]	48[−3]
3629	1907	$9/2^-$	$5/2^-$	$B(E2)$	0.81(22)	0.89
	3129		$7/2^-$	$B(M1)$	11(3)[−3]	136[−3]
4006	1850	$3/2^+$	$1/2^+$	$B(M1)$		6.8[−3]
				$x(E2/M1)$		+0.67
				Γ_γ (eV)		2.04[−3]
	2526			$B(M1)$	>0.55	1.2
				$x(E2/M1)$		−0.03
				Γ_γ (eV)		80.9[−3]
5170	1907	$9/2^+$	$5/2^+$	$B(E2)$	>15	8.3
	3129		$7/2^-$	$B(E1)$	>2[−3]	2.2[−3]

[a]$B(L)$ values are in Weisskopf units (Ref. 37), radiative widths (Γ_γ) are in eV, and $x(L+1/L)$ is defined as $[\Gamma_\gamma(L+1)/\Gamma_\gamma(L)]^{1/2}$ with the sign convention of Rose and Brink (Ref. 38).

[b]The uncertainty in the last figure is in parentheses. The number in square brackets is the power of 10.

from the weak-coupling structure of the levels and the strong $3/2^+ \rightarrow 5/2^+$ $M1$ transition between the members of the ^{19}F g.s. band.[24]

For three of the five listed $E1$ transitions, the agreement of the predictions to experiment is satisfactory considering the nature of these decays. For the $1/2_1^+ \rightarrow 1/2_1^-, 3/2_1^-$ $E1$ rates, the disagreement is very marked with predictions some 100 and 36 times too large, respectively. The $1/2^+ \rightarrow 1/2^-$ decay was examined in some detail in order to better understand the nature of this disagreement. As expected, the matrix element was found to result from strong cancellation between various components. For instance, if we group the contributions as

$$M(1/2_1^+ \rightarrow 1/2^-) = M[0d \rightarrow 0p] + M[1s \rightarrow 0p] + M[(0f,1p) \rightarrow (1s,0d)] \quad (1)$$

we find

$$M(1/2_1^+ \rightarrow 1/2^-) = +0.2161 - 0.0356 - 0.1515 = +0.029 \ . \quad (2)$$

Because of the large matrix elements for $(0f,1p) \rightarrow (2s,0d)$ transitions, the small admixture of $(0f,1p)$, 1.3%, in the $1/2_1^+$ state has a large effect; it decreases the $E1$ rate by a factor of ~ 39. It is not surprising that the $E1$ rates are difficult to predict reliably.

4. $^{17}C(\beta^-)^{17}N$

The beta decay of ^{17}C has been investigated by Curtin *et al.*,[39] who measured a half-life of 202(17) ms, and by Dufour *et al.*,[8] who obtained a half-life of 220(80) ms and, most important, observed beta-delayed γ transitions in ^{17}N, albeit with poor statistics. The results of Dufour *et al.* consist of energies and relative intensities for five γ transitions. These can be placed in the decay scheme of Fig. 3(a). The decay scheme of Fig. 3(b) shows the γ

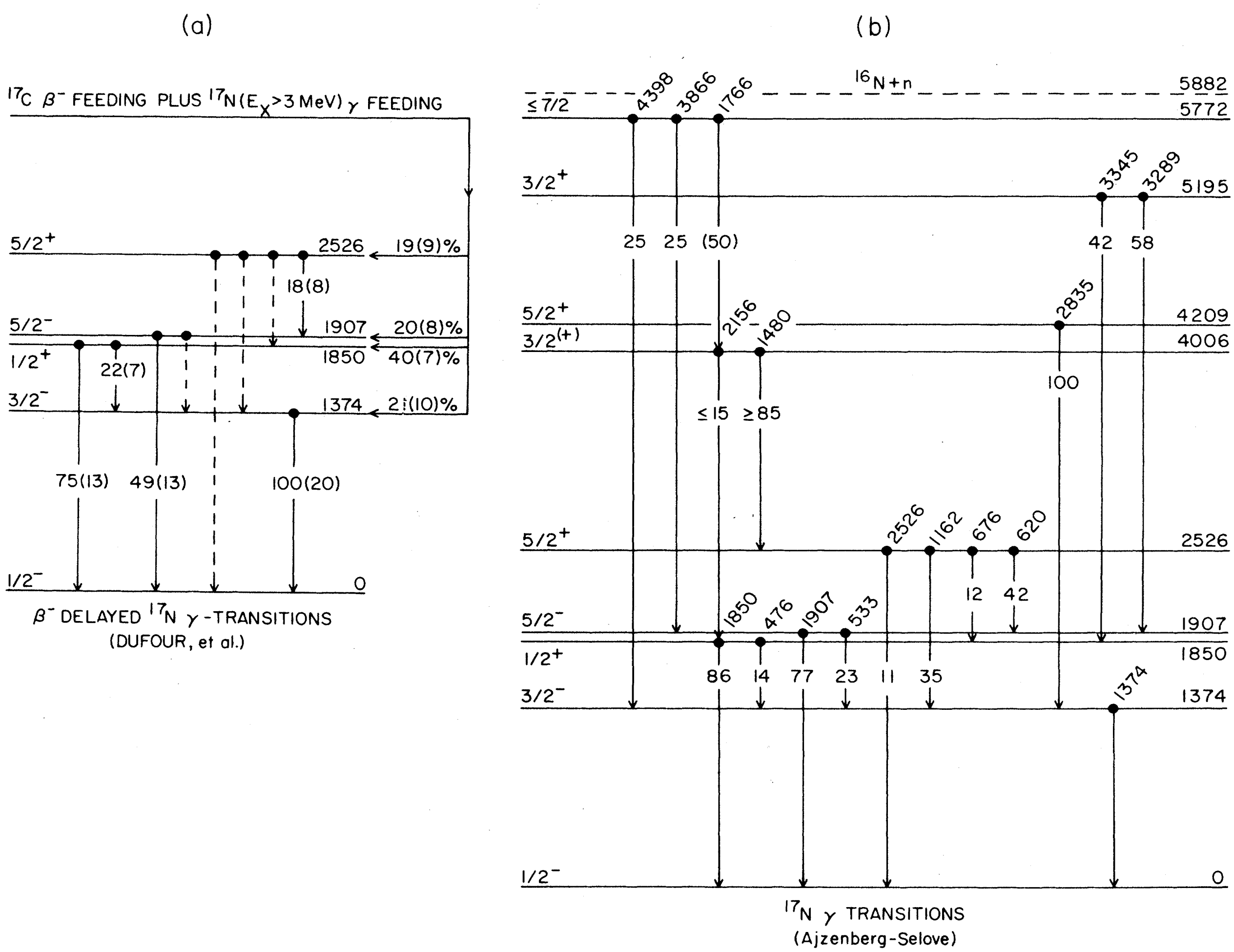

FIG. 3. (a) The results of Dufour *et al.* (Ref. 8), which consist of a list of five γ-ray energies and relative intensities, placed in a decay scheme. (b) γ-ray decay scheme for the bound levels of ^{17}N from Ref. 22. All known levels with $E_x < 3$ MeV are shown. Above 3 MeV only possible even-parity bound levels with $J < 9/2$ are shown.

branches of all known ^{17}N levels below 3 MeV excitation and the possible γ-emitting $J^{\pi}<9/2^{+}$ levels above 3 MeV. Figure 3(b) is necessary for the interpretation of Fig. 3(a). A comparison of Figs. 3(a) and (b) shows that four γ transitions are missing from the decays of the four excited states shown in Fig. 3(a). These missing decays, indicated by dashed lines in Fig. 3(a), were taken into account in constructing the feeding intensities shown to the right in Fig. 3(a). Presumably, these four transitions were overlooked because of the poor statistics. Since γ cascades from levels at >3 MeV excitation could also easily have been overlooked, the feeding shown to the right is interpreted as due to the sum of γ cascades from 3 MeV $<E_x<5.9$ MeV plus that of β feeding. It is these feeding intensities and the total half-life which we can compare to our model predictions.

Only even-parity states above 3.6 MeV are included in Fig. 3(b) because our calculations show clearly that first-forbidden decays are negligible for $E_x>3$ MeV. The largest feeding intensity shown in Fig. 3(a) is to the $1/2_1^+$ state. Referring to Fig. 3(b), there is only one definite and one possible γ cascade from the four levels above 2.6 MeV to the $1/2_1^+$ state. Consideration of the possible intensities of these and other branches leads to the conclusion that the $1/2^+$ state is almost certainly direct fed in ^{17}C β^- decay. Thus, the ^{17}C g.s. is most likely $1/2^+$ or $3/2^+$. Nevertheless, in what follows, we shall assume $J^{\pi}=1/2^+$, $3/2^+$, or $5/2^+$ for the ^{17}C ground state and consider allowed β decay to $J^{\pi}<9/2^+$ states in ^{17}N. The four states shown for $E_x>3$ MeV are the only possible $J^{\pi}<9/2^+$ known states with 3 MeV $<E_x<6$ MeV. However, assuming as we do that the 5170 keV level has $J^{\pi}=9/2^+$, inspection of Fig. 2 indicates that several other $J^{\pi}<9/2^+$ states may be below the ^{16}N$+n$ threshold at 5.88 MeV.

For all three assumed ^{17}C spins, the allowed beta decay was calculated for all ^{17}N states predicted to be energetically accessible, and first-forbidden decay was calculated for the lowest-lying ten states of each possible spin. For the states below 5.6 MeV excitation, the experimental ^{17}N energies (when known) of Fig. 2 were used in the calculations. For the other levels, the model energies, shifted as shown in Fig. 2, were used. The ground-state Q value was taken to be 13165(23) keV which results from the weighted average of the three ^{17}C mass excess measurements listed by Fifield *et al.*[21]

We anticipate the results for first-forbidden transitions to note that the only first-forbidden branch $>1\%$ was found to be the $1/2^+\rightarrow 1/2_1^-$, $3/2^+\rightarrow 3/2_1^-$, or $5/2^+\rightarrow 5/2_2^-$ decay, depending on the ^{17}C ground-state spin value. These are all overwhelmingly rank zero in nature, as expected from the systematics of first-forbidden decays.[19,40]

The results of the calculations are summarized in Table III. Because of the difference between the predicted and experimental half-life, there is an ambiguity in how the allowed and first-forbidden partial half-lives are combined to obtain branching ratios to individual states. Our approach is to define a first-forbidden branch BR(FFB), in terms of the total predicted first-forbidden partial half-life, $t_{1/2}$ (FFB), and the experimental half-life, $t_{1/2}(\text{expt})=202$ ms, as

$$\text{BR(FFB)}=100t_{1/2}(\text{expt})/t_{1/2}(\text{FFB}) .$$

Then we define the allowed partial branching ratio, BR(GT)$=100-$BR(FFB).

Comparison of the predicted results of Table III to the experimental $(\beta+\gamma)$ feeding intensities of Fig. 3(a) is made by dividing the predicted branching ratios by

TABLE III. Predicted β^- branching ratios, half-lives, and P_n values (fraction of decays leading to neutron-unstable states). The ^{17}N excitation energies, E_x, of the last four listed states are the model predictions of Fig. 1; the rest are experimental. The experimental half-life is 202(30) ms, and the experimental value of P_n is <0.11. The half-lives given at the bottom of the table are in milliseconds.

^{17}N state		β^- branching ratio			logft		
J_n^{π}	E_x (keV)	^{17}C $(1/2^+)$	^{17}C $(3/2^+)$	^{17}C $(5/2^+)$	^{17}C $(1/2^+)$	^{17}C $(3/2^+)$	^{17}C $(5/2^+)$
$1/2_1^-$	0	17.7	0.3	0.8	5.78	7.50	7.14
$3/2_1^-$	1374	0.5	4.3	0.4	7.09	6.25	7.24
$1/2_1^+$	1850	23.0	27.3		5.73	5.37	
$5/2_1^-$	1907	0.0	0.2	0.5	11.33	7.36	6.99
$5/2_1^+$	2526		8.4	21.4		5.75	5.50
$5/2_2^-$	3906	0.0	0.0	1.3	8.51	8.32	6.20
$3/2_1^+$	4006	3.3	15.7	36.9	6.15	5.17	4.95
$5/2_2^+$	4209		4.0	1.5		5.72	6.18
$3/2_2^+$	5195	0.0	3.0	0.5	7.86	5.60	6.57
$3/2_3^+$	5000	11.8	4.1	7.6	5.35	5.52	5.39
$1/2_2^+$	5030	1.3	1.2		6.32	6.03	
$5/2_3^+$	5360		0.2	2.1		6.66	5.85
$7/2_1^+$	5575			6.2			5.32
$t_{1/2}$ (FFB)	=	1110	4210	6590			
$t_{1/2}$ (GT)	=	595	263	364			
$t_{1/2}$	=	387	249	345			
P_n	=	0.42	0.31	0.22			

$1-P_n-BR_{g.s.}$, and calculating the γ feeding from the γ branching ratios of Fig. 3(b) and the β branching ratios of Table III. The fraction of decays leading to neutron-emitting states is denoted as P_n and the β^- branch to the ground state by BR g.s. In doing so we assume (arbitrarily) a 100% 4006→2526 branch for $J^\pi(^{17}C)=1/2^+$ or $3/2^+$ (but not, in order to get the limits in Table IV, $5/2^+$), a $3/2_3^+$ assignment for the 5772 keV level, and no uncertainties in the branching ratios of the four levels above 3 MeV in Fig. 3(b). These assumptions, made for simplicity, have little effect on the results which are shown in Table IV.

We are interested in whether the results of Tables III and IV can be used to obtain a model-dependent spin-parity assignment for ^{17}C. From Table IV, it is clear that the $J^\pi(^{17}C)=5/2^+$ alternative is highly disfavored. There is much too little feeding of $3/2_1^-$ and $1/2_1^+$ and too much for $5/2_1^+$. Considering the γ-ray branching ratios of Fig. 3(b), it is hard to see how the large feeding observed for the $1/2_1^+$ state can be obtained for $J^\pi(^{17}C)=5/2^+$. We conclude that $J^\pi(^{17}C)=5/2^+$ is highly disfavored independent of any model, and is eliminated model dependently. This is consistent with the conclusions reached in our analysis of energy-level systematics in Sec. III A.

From Table III, we see that the $J^\pi=3/2^+$ assumption results in a predicted half-life in good agreement with experiment, while the $1/2^+$ assumption gives a half-life a factor of 2 too long. The feeding intensities for both the $1/2^+$ and $3/2^+$ assumptions are in poor agreement with experiment. This is also true for P_n, the fraction of decays proceeding to states above the neutron threshold. A recent measurement of $P_n<0.11$ has been reported.[41] This is considerably less than the predicted values. Although a $J^\pi=3/2^+$ assignment to the ^{17}C ground state is favored to some extent by this comparison, we feel that both alternatives are quite possible. Clearly, more experimental work must be done before a definitive test of our model predictions can be made. To this end, the following information is needed: (1) definite spin-parity assignments for all the states below the $^{16}N+n$ threshold, (2) accurate γ-branching ratios for the states in the 3 MeV $<E_x<5.9$ MeV region, and (3) high statistic β^--delayed γ spectra. It would also be desirable to have measurements of the β^- branch to the ^{17}N ground state and of P_n. The ground-state branching ratio, in particular, is capable of differentiating between the $1/2^+$ and $3/2^+$ alternatives for the ^{17}C ground state.

APPENDIX: THE EXPERIMENTAL ^{17}N ENERGY SPECTRUM

We are interested here in the γ-emitting, i.e., particle-bound, states of ^{17}N since it is these which can influence the interpretation of the ^{17}C decay data. The ^{17}N neutron threshold is at 5.88 MeV. A complete survey of the γ-emitting states has, in principle at least, been made via the $^{11}B(^7Li,p\gamma)^{17}N$ reaction.[42,43] As reviewed in Ajzenberg-Selove's latest compilation,[22] there are 16 ^{17}N excited states below 5.88 MeV excitation, and all states have known γ-decay modes. Nine states are given definite spin-parity assignments. These assignments come mainly from spin restrictions implied by γ-ray branching ratios, angular correlations, and lifetime measurements or limits[42–44] combined with orbital angular momentum transfers deduced from $^{18}O(d,^3He)^{17}N$ (Ref. 34) and $^{15}N(t,p)^{17}N$ (Ref. 45) angular distributions. Analyzing powers from the $^{18}O(\vec{d},^3He)^{17}N$ reaction[46] provide unique spin assignments for four excited states below the neutron threshold. For some of the other states very probable assignments can be made. We explain our choices from the alternatives listed in the compilation[22] here.

The 3629 keV level with $J^\pi=7/2^-$ or $9/2^-$ is strongly formed,[47] along with the $7/2^-$ 3129 keV level, in the two-nucleon transfer reaction $^{15}N(^{13}C,^{11}C)^{17}N$. The heavy-ion reaction favors high angular momentum transfer and, from the systematics of such reactions,[47] the two states can be identified as the $7/2^-$ and $9/2^-$ members of a doublet formed by $L=4$ transfer, as is also found in the $^{15}N(t,p)^{17}N$ reaction.[45] In our view, this work strongly supports a $9/2^-$ assignment. Further supporting evidence for this assignment comes from the $M2$ excitation of the probable analog in ^{17}O in the $^{17}O(e,e')^{17}O$ reaction.[48]

From the discussion of Sec. III B 1, only two $3/2^-$ states are expected below the predominantly $p_{3/2}^{-1}\otimes{}^{18}O(0_1^+)$ level at 5515 keV. Since $3/2^-$ levels have been

TABLE IV. Comparison of the model derived $(\beta^-+\gamma)$ feeding of the first four excited ^{17}N states to the experimental results of Fig. 3(b).

^{17}N state J_n^π	E_x (keV)	$(\beta^-+\gamma)$ feeding (%) ^{17}C $(1/2^+)^a$	^{17}C $(3/2^+)^a$	^{17}C $(5/2^+)^a$	Expt.
$3/2_1^-$	1374	9	14	4	21(10)
$1/2_1^+$	1850	58	42	$<8^b$	40(7)
$5/2_1^-$	1907	7	4	$<14^c$	20(8)
$5/2_1^+$	2526	23	38	81	19(9)

[a]The present branches do not add to 100% because all the states predicted below the $^{16}N+n$ threshold have not been observed (see Fig. 2).
[b]The limit corresponds to an assumed $\leq 15\%$ branch for $3/2_1^+\rightarrow 1/2_1^+$.
[c]The limit corresponds to the assumption of 100% $5/2_3^+\rightarrow 5/2_1^-$ and $7/2_1^+\rightarrow 5/2_1^-$ branches.

identified at 1274 and 3204 keV, this suggests the $5/2^-$ alternative for the states at 3906 and 4415 keV with $J^\pi=3/2^-$ or $5/2^-$. The $5/2^-$ assignments are consistent with the fact that the observed γ decays are to the $5/2^-$ 1907 keV level with no observed branch to the $1/2^-$ ground state. Fortune *et al.* also favor these assignments.[45]

The 4006 keV level with $J=3/2$ is formed by a most probable $L=1$ assignment in the $^{15}N(t,p)^{17}N$ reaction,[45] implying a positive-parity assignment. This is consistent with the weak-coupling argument regarding the number of low-lying $3/2^-$ levels. On the other hand, Mairle *et al.*[34] assigned a tentative $l_p=1$ pickup to the formation of this state via the $^{18}O(\vec{d},{}^3He)^{17}N$ reaction. A level at 4.01 MeV is strongly excited, along with states at 2.53 and 5.17 MeV, in the $^{14}C(^6Li,{}^3He)^{17}N$ reaction.[49] Cunsolo *et al.*[49] interpreted these states as the $5/2^+$, $3/2^+$, and $9/2^+$ members (in order of increasing excitation energy) of a $^{14}C(0^+)\otimes{}^{19}F(J^\pi)$ band. The triton spectroscopic factors determined[49] for the $5/2^+$ and $3/2^+$ states are similar in magnitude, in agreement with the values obtained from our shell-model wave functions. We conclude that a $3/2^+$ assignment is strongly favored for the 4006 keV level. The argument for a $9/2^+$ assignment[42,45] to the 5170 keV level is strengthened by the triton transfer data.

The 5195 keV level has been assigned[22,45] $J^\pi=1/2^+$ or $3/2^+$. We note that the $1/2^+$ assignment can be definitely excluded since, when combined with the lifetime limit and γ-branching ratios, it would demand[42] an $M2$ strength for decay to the $5/2^-$ 1907 keV level of >100 W.u.

The $^{15}N(t,p)^{17}N$ angular distribution for the 5772 keV level is very well fitted for an $L=1$ transfer, implying[45] $J^\pi=1/2^+$ or $3/2^+$. For $J^\pi=1/2^+$, the $M2$ strength[42] for decay to the $5/2^+$ 1907 keV level is >12 W.u. While this does not rule out the $1/2^+$ assignment, a $3/2^+$ assignment is more likely.

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