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# THE THREE PARTICLE STRUCTURE OF $^{19}$F

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**Abstract:** A detailed comparison is made between over 100 experimental decay strengths from positive parity states in $^{19}$F and the predictions of $(sd)^3$ shell model calculations using Kuo or Kallio-Kolltveit matrix elements. It is shown that the $K = \frac{1}{2}^+$ and $\frac{3}{2}^+$ bands (except for the 3907 keV level), along with several other levels, can be explained by these calculations. The levels at 3907, 5336 and 5497 keV are shown to be intruder states. Emphasis is placed on showing where the predictions are sensitive to the residual interaction used.

## 1. Introduction

Historically $^{19}$F has played an important role in shell model calculations since one of the first full intermediate coupling calculations was done in 1955 by Elliott and Flowers for the positive parity states of $^{19}$F [ref. [1]]. At that time only 3 levels of positive parity had been identified but the results of the calculations were very encouraging. In the years since, the properties of many more positive parity states have been established experimentally [2] (the spins and $\gamma$-decays of over 25 positive-parity levels are now known) and many theoretical studies [3-6] have further confirmed the ability of the shell model to explain the properties of the ground state band.

With the advent of large, generalized shell model codes [7], the computational complexities of the shell model are no longer as important as the problems of discovering suitable truncation schemes and finding the appropriate residual interaction. Even near the beginning of the (sd) shell the former problem is formidable. For all but the lowest states, particle-hole excitations are important in most nuclei (e.g. a 4p-2h state occurs at 1.70 MeV in $^{18}$F) and require prohibitively large basis sets for the complete shell model calculations unless truncation schemes are employed. Adding to the problem of finding suitable truncations is the unreliability of the residual interaction, which, as has been dramatically pointed out in the case of $^{28}$Si [ref. [8]], can mask an inadequacy in the truncation scheme. This means, for example, that in the case of $^{18}$F, slight discrepancies between the predictions of an $(sd)^2$ shell model and the experimental results may be due either to the use of a poor residual interaction or to small 4p-2h components in the wave functions. This ambiguity makes it difficult to isolate and correct shortcomings in the residual interaction.

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Whether these ambiguities arise in $^{19}$F has not been discussed in light of the recent experimental information. This paper will present a detailed comparison of the experimental data and the predictions of the $(sd)^3$ shell model with emphasis on: (i) what experimental data is available; (ii) how much of it can be understood within the framework of the $(sd)^3$ shell model; (iii) where the predicted observables are sensitive to the residual interaction used; and (iv) which missing data may provide more stringent tests of the models. It will be shown that the properties of over 16 levels are well described by this model with only 3 clear intruder states of positive parity below 6.2 MeV. It will also be shown that the properties of several levels are very sensitive to the residual interaction used. The good agreement for so many levels and the observed sensitivity of the calculations imply that $^{19}$F may provide a very stringent test for the (sd) shell residual interaction. The extent to which this can be shown to be true will be discussed in sects. 2 and 10.

As well as being described by the shell model, $^{19}$F has frequently been described by the rotational model. The properties of the low-lying levels of $^{19}$F were first explained in terms of strongly mixed $K = \frac{1}{2}^+$ and $K = \frac{3}{2}^+$ bands [9]) although recent theoretical work on the interpretation of the $K = \frac{1}{2}^+$ band [5]) indicated mixing was of less importance. However, even more recent work with the $^{16}$O($^6$Li, $^3$He)$^{19}$F reaction [10]) has cast doubts on which levels belong to which band, while Nilsson model calculations [11]) which include all 6 bands in the (sd) shell have again stressed the need to include mixing. Dixon *et al.* [12]) have postulated that the suggested $K = \frac{3}{2}^+$ band (including the 3.91 ($\frac{3}{2}^+$), 4.55 ($\frac{5}{2}^+$), 5.46 ($\frac{7}{2}^+$), 6.59 ($\frac{9}{2}^+$) and 7.94 ($\frac{11}{2}^+$) MeV levels) had 5p-2h or 7p-4h character since the $\frac{3}{2}^+$ band head could not be explained in the $(sd)^3$ shell model and the moment of inertia for the band was similar to that of the $K = \frac{3}{2}^+$ ground state bands of $^{21}$Ne and $^{23}$Na. However, it was noted that the relatively strong cross-band M1 transitions implied an $(sd)^3$ component in the wave functions. Garrett and Hansen [11]) have suggested that in fact the entire band can be explained in terms of a Nilsson model restricted to particles in the (sd) shell. It will be shown below that similar conclusions and much better agreement with the data can be achieved using the $(sd)^3$ shell model except that the $\frac{3}{2}^+$ level at 3907 keV is not explained.

## 2. Criteria for $(sd)^3$ states

A level will be referred to as an $(sd)^3$ state if its known properties are explained by considering it as three particles in the (sd) shell outside an inert $^{16}$O core. The emphasis is on "inert core" rather than closed shell since calculations indicate that only $\approx 80\,\%$ of the $^{16}$O ground state has a closed p-shell [13]). It is a more difficult task to prove a given level is an $(sd)^3$ state. Stripping, pick-up and multiparticle transfer reactions are very useful indicators in this respect but are subject to very strong fluctuations in cross section which depend on more than just whether or not the state is $(sd)^3$ in nature, and furthermore assignments are dependent on models of the ground state of the target nucleus and models for any transferred groups of particles. Likewise $\gamma$-decay data can never prove an $(sd)^3$ assignment since there may be large intruder configurations in the "correct" wave function which do not influence the predicted decay rates. Thus a comparison of theory and experiment allows only the following conclusions to be drawn:

(i) If *no* residual interaction can reproduce a given observation, then the truncation scheme used is wrong.

(ii) Gamma decays between levels imply each state has a component differing by at most one particle in different major shells (i.e. a 7p-4h or 5p-2h state cannot decay to a three-particle state unless there is mixing since one normally assumes electromagnetic operators are one-body operators).

The weakness of these conclusions leads to an ambiguity between shortcomings in the truncation scheme versus shortcomings in the residual interaction. Thus if one residual interaction predicts the properties of a nucleus better than another, this does not imply it is necessarily the "more realistic" interaction, in the sense that it uses a more nearly correct nucleon-nucleon potential. The shortcomings of one residual interaction may be due to renormalization effects in that particular basis which do not occur in a different basis.

These comments have been made to serve as a warning against interpreting the following comparisons too superficially. The facts are that the predicted properties of some states in $^{19}$F are sensitive to the residual interaction used in the calculations and that one particular interaction gives better overall agreement with experiment. This may be telling us something fundamental about the residual interaction or it may merely be pointing out where other configurations are becoming important. No attempt will be made to resolve this ambiguity in the present paper, but merely to draw attention to where it occurs.

## 3. The calculations

Two sets of shell model results will be quoted extensively. The first were done by the author using the Rochester-Oak Ridge code [7]*. The "realistic" matrix elements of Kuo [15] were employed. These results are exactly the same as, and extend the K + $^{17}$O results of ref. [4]). The second set of results are those of Benson and Flowers [ref. [5]]** in which the Kallio-Kolltveit residual interaction was employed and Woods-Saxon radial wave functions were used to calculate E2 transition strengths (but not the wave functions). These calculations will be referred to as the K + $^{17}$O and KK calculations respectively. Since both sets of calculations are described in the literature, no detail will be given here.

Emphasis in this paper will be on showing where the theoretical calculations are

* I am indebted to Dr. S. S. M. Wong for explaining at great length the intricacies of the code.

** I wish to thank Dr. H. G. Benson for providing his complete computer output which included far more than was originally published.

sensitive to the residual interaction used, and in this sense there is no special emphasis placed on the particular matrix elements used. The two sets of calculations presented have been chosen both for their availability and for the fact that they display this sensitivity well. The matrix elements have been derived using two different approaches. The Kuo matrix elements are based on the Hamada-Johnson nuclear potential derived from nucleon-nucleon scattering results. A renormalization procedure was applied to the bare matrix elements to take into account core polarization effects for the $^{18}$O system. In contrast to this "realistic" set of matrix elements, the Kallio-Kolltveit matrix elements are based on a phenomenological hard-core potential designed to fit the scattering length and binding energy of the deuteron. No renormalization effects have been explicitly taken into account and these matrix elements are purely central in nature compared to the Kuo matrix elements which contain tensor components.

It will be shown that the KK calculations frequently give stronger E2 strengths between states outside the $K = \frac{1}{2}^+$ band. This may be a function of the residual interaction used or the fact that Woods-Saxon radial integrals were used in calculating the transition rates. If the latter effect is the cause of this improved agreement, this points out the importance of using Woods-Saxon integrals for E2 rates between states in which collective motions are not dominant.

## 4. The data

The data for $^{19}$F have recently been summarized in ref. [2]. In what follows, several recent results have also been included [refs. [16-19]], and additional data (e.g. mixing ratios) have normally been taken from the same sources as quoted in ref. [2] [*viz.* refs. [20,21]].

Spin and parities are, in general, firmly established for the first two levels of a given spin but beyond that the evidence is often more tenuous. The levels for which the $J^\pi$ assignment is uncertain are shown as dashed lines in figs. 1 and 4 and are discussed briefly at the beginning of each section.

## 5. Discussion of individual levels

### 5.1. THE $J^\pi = \frac{1}{2}^+$ LEVELS

*5.1.1. The data.* The levels at 5336 and 5938 keV have been assigned $J = \frac{1}{2}$ [refs. [16,22]]. Positive parity has been established for the latter [16,23] and is likely for the former since its apparent analogue in $^{19}$Ne has positive parity [25]. The levels at 6250 and 7364 keV have been observed in the $^{18}$O($^3$He, d)$^{19}$F reaction but their $\gamma$-decays are unreported.

*5.1.2. Comparison with theory.* (See table 1 and fig. 1.) The observed spectroscopic factors of the g.s. and 6250 keV levels lead to their association with the $\frac{1}{2}^+_1$ and $\frac{1}{2}^+_3$ states † in either calculation although the eigenvalue is better reproduced in

† $J_i^\pi$ will be used to denote the $i$th theoretical state of spin-parity $J^\pi$.

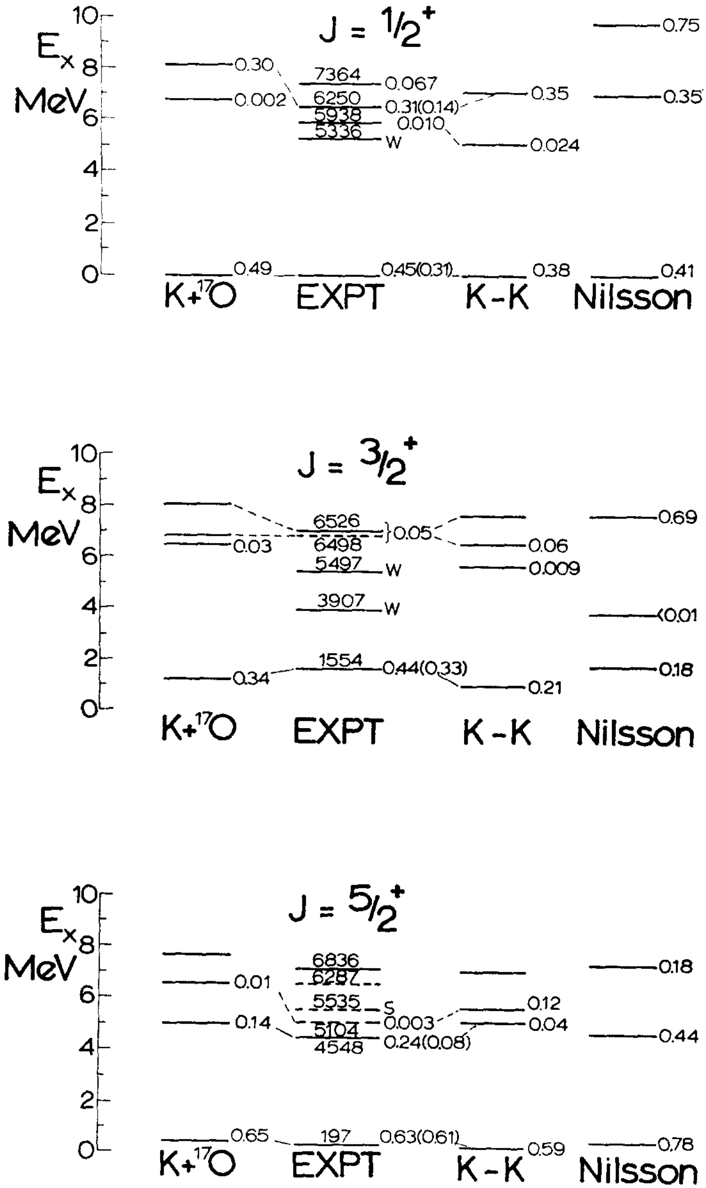


Fig. 1. Comparison of theoretical versus experimental excitation energies and spectroscopic factors in the $^{18}O(^{3}He, d)^{19}F$ reaction for the $\frac{1}{2}^+$, $\frac{3}{2}^+$ and $\frac{5}{2}^+$ levels in $^{19}F$. Dashed experimental levels imply the spin or parity assignments are tentative. Experimental values of $S$ are from refs. [23,24]). A W or an S means the level was weakly or strongly fed but no spectroscopic factor was obtained. States for which firm correspondences can be made in view of $\gamma$-decay rates and spectroscopic factors are joined by a solid line and partial or tentative correpondences are shown by a dashed line. The K+$^{17}$O and KK results are from (sd)$^3$ shell model calculations using $^{17}$O single-particle energies and Kuo or Kallio-Kolltveit matrix elements respectively. The Nilsson model results are those of ref. [11]) including all six (sd) shell bands.

TABLE 1

Comparison of predicted and observed transition strengths from $J^{\pi} = \frac{1}{2}^+$ levels in $^{19}$F (in W.u.)[a])

| Experiment | | | Theory | | | | |
|---|---|---|---|---|---|---|---|
| | | | | KK | | K+$^{17}$O | |
| transition | M1 | E2 | transition | M1 | E2 | M1 | E2 |
| 5336 → 0($\frac{1}{2}^+$) | 0.18±0.03 | | | | | | |
| → 1554($\frac{3}{2}^+$) | <0.03 | | | | | | |
| → 197($\frac{5}{2}^+$) | | <2 | | | | | |
| 5938 → 0($\frac{1}{2}^+$) | (8.4±4)×$10^{-3}$ | | $\frac{1}{2}{}_2^+ \to \frac{1}{2}{}_1^+$ | 5×$10^{-3}$ | | 5×$10^{-4}$ | |
| → 1554($\frac{3}{2}^+$) | <0.006 | | $\to \frac{3}{2}{}_1^+$ | 0.04 | 1.02 | 0.009 | 0.042 |
| → 3907($\frac{3}{2}^+$) | 0.24±0.10[b]) | | $\to \frac{3}{2}{}_2^+$ | 0.72 | 0.009 | 0.04 | 1.19 |
| → 197($\frac{5}{2}^+$) | | 0.7±0.4 | $\to \frac{5}{2}{}_1^+$ | | 0.87 | | 0.009 |
| | | | $\frac{1}{2}{}_3^+ \to \frac{1}{2}{}_1^+$ | 2×$10^{-5}$ | | | |
| | | | $\to \frac{3}{2}{}_1^+$ | 0.002 | 0.008 | | |
| | | | $\to \frac{3}{2}{}_2^+$ | 2.19 | 0.79 | | |
| | | | $\to \frac{5}{2}{}_1^+$ | | 2.53 | | |

[a]) Here and in tables 2–7, theoretical-experimental correspondences are *not* necessarily implied by horizontal alignment. See text and figures for these correspondences.

[b]) Assumed pure M1.

the KK calculation. These associations for the $\frac{1}{2}{}_1^+$ and $\frac{1}{2}{}_3^+$ state imply that one of the 5336 or 5938 keV levels should be associated with the $\frac{1}{2}{}_2^+$ state. The strong M1 decay from the 5336 keV level cannot be explained using either calculation indicating that the level is not likely an $(sd)^3$ state. This is consistent with the strong E1 decays observed from this level and its large reduced α-width of ≈ 9 %, both of which would be forbidden from a pure $(sd)^3$ state (see sect. 6). This leaves the 5938 keV level to be associated with the $\frac{1}{2}{}_2^+$ state and the KK $\frac{1}{2}{}_2^+$ state does give a reasonable description of the γ-decay of the state. However, the description is not as good as it appears to be, since the 3907 keV level is probably an intruder state (see sect. 5.2). The strong M1 transition to the 3907 keV level then implies that the 5938 keV level must have a sizable deformed component as well as any $(sd)^3$ component. This could be interpreted as mixing with the nearby 5336 keV intruder state. Even if the 3907 keV level is not an intruder the decays of the $\frac{1}{2}{}_2^+$ state are of interest since they are very sensitive to the residual interaction which is used.

### 5.2. THE $J^{\pi} = \frac{3}{2}^+$ LEVELS

*5.2.1. The data.* The 3907 keV level is known to have spin $\frac{3}{2}$ [ref. [20])] and positive parity can be tentatively assigned since its apparent analogue in $^{19}$Ne at 4013 keV has $J^{\pi} = \frac{3}{2}^+$ [ref. [26])]. The branching ratios used here come from a recent study [27]) and are mid-way between those reported previously [18,20]). The levels at 6498 and 6526 keV both have spin $\frac{3}{2}$ but only the latter is definitely assigned positive parity [17]).

*5.2.2. Comparison with theory.* (See table 2 and figs. 1 and 2.) The 1554 keV level is well explained by both sets of calculations and the strong preference for decay to the $J+1(\frac{5}{2}^+)$ level as opposed to the $J-1(\frac{1}{2}^+)$ level [also observed from the $\frac{11}{2}^+$ and

TABLE 2

Comparison of predicted and observed transition strengths from $J^{\pi} = \frac{3}{2}^+$ levels in $^{19}$F (in W.u.)

| Experiment | | | Theory | | | | |
|---|---|---|---|---|---|---|---|
| | | | | KK | | K+$^{17}$O | |
| transition | M1 | E2 | transition | M1 | E2 | M1 | E2 |
| 1554 → 0($\frac{1}{2}^+$) | 0.04±0.02 | 6.8±0.7 | $\frac{3}{2}{}_1^+ \to \frac{1}{2}{}_1^+$ | 0.012 | 7.2 | 0.004 | 6.4 |
| → 197($\frac{5}{2}^+$) | 2.7±1.4 | <127 | $\to \frac{5}{2}{}_1^+$ | 2.1 | 2.3 | 1.8 | 2.8 |
| 3907 → 0($\frac{1}{2}^+$) | >0.015$^{a}$) | | $\frac{3}{2}{}_2^+ \to \frac{1}{2}{}_1^+$ | 0.009 | 0.14 | 0.002 | 0.77 |
| → 1554($\frac{3}{2}^+$) | >0.022$^{a}$) | | $\to \frac{3}{2}{}_1^+$ | 0.013 | 0.32 | 0.007 | 0.16 |
| → 197($\frac{5}{2}^+$) | >0.003$^{a}$) | | $\to \frac{5}{2}{}_1^+$ | 0.006 | 0.36 | 0.003 | 0.03 |
| 5497 → 0($\frac{1}{2}^+$) | (<0.06)$^{b}$) | | $\to \frac{5}{2}{}_2^+$ | 0.29 | 1.0 | 1.2 | 0.33 |
| → 1554($\frac{3}{2}^+$) | 0.34±0.10$^{a}$) | | $\frac{3}{2}{}_3^+ \to \frac{1}{2}{}_1^+$ | 0.002 | 2.7 | 0.073 | 0.03 |
| → 197($\frac{5}{2}^+$) | 0.26±0.08 | <2.4 | $\to \frac{3}{2}{}_1^+$ | 0.024 | 1.3 | 0.003 | 0.13 |
| 6498 → 0($\frac{1}{2}^+$) | 0.06±0.01 | <0.12 | $\to \frac{5}{2}{}_1^+$ | 0.004 | 0.99 | 0.03 | 0.10 |
| | or 0.011±0.002 | 9±2 | $\to \frac{5}{2}{}_2^+$ | 1.07 | 0.0005 | 0.32 | 1.1 |
| → 1554($\frac{3}{2}^+$) | <0.004 | | $\to \frac{5}{2}{}_3^+$ | 0.59 | 2.64 | 0.47 | 0.14 |
| → 197($\frac{5}{2}^+$) | <0.017$^{c}$) | <3 | | 0.056 | $2\times10^{-4}$ | 0.02 | 0.001 |
| 6526 → 0($\frac{1}{2}^+$) | 0.053±0.009 | 1.1±0.3 | $\frac{3}{2}{}_4^+ \to \frac{1}{2}{}_1^+$ | 0.013 | 0.77 | 0.007 | 0.02 |
| | or 0.032±0.006 | 5±1 | | | | | |
| 6526 → 1554($\frac{3}{2}^+$) | <0.02 | | $\to \frac{3}{2}{}_1^+$ | | | | |
| → 3907($\frac{3}{2}^+$) | <0.15 | | $\to \frac{3}{2}{}_2^+$ | | | 0.004 | 1.59 |
| → 197($\frac{5}{2}^+$) | <0.008 | | $\to \frac{5}{2}{}_1^+$ | 0.028 | 0.003 | 0.002 | 0.10 |
| → 4548($\frac{5}{2}^+$) | 0.85±0.20 | 100±80 | $\to \frac{5}{2}{}_2^+$ | 0.009 | 4.5 | 0.14 | 1.38 |
| → 5104($\frac{5}{2}^+$) | <0.7 | | $\to \frac{5}{2}{}_3^+$ | 0.30 | 0.36 | 0.11 | 0.48 |

$^{a}$) Assumed pure M1.
$^{b}$) Not reported but 10 % limit on branch assumed.
$^{c}$) Seen but mixing ratio not defined.

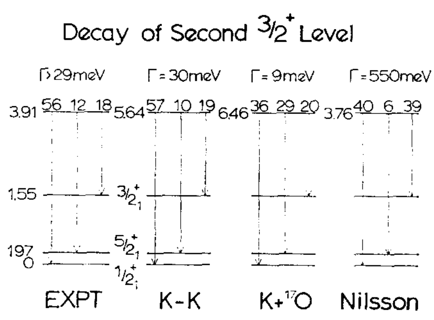


Fig. 2. Comparison of experimental and predicted decay schemes to positive parity levels from the second $\frac{3}{2}^+$ level.

$\frac{7}{2}^+$ levels at 7937 and 5464 keV] is explained by reference to the *L-S* coupling scheme [refs. [3,4])]. The $\frac{5}{2}^+$ and $\frac{3}{2}^+$ levels have predominantly $L = 2$ configurations while the $\frac{1}{2}^+$ level has an $L = 0$ configuration [1]). Since the major component in the M1 operator only connects configurations with $\Delta L = 0$, the $\frac{3}{2}^+ \rightarrow \frac{5}{2}^+$ transition is much stronger than the $\Delta L = 2$ $\frac{3}{2}^+ \rightarrow \frac{1}{2}^+$ transition.

Beyond the first $\frac{3}{2}^+$ level all identifications become very tenuous. The predicted and observed weakness of the spectroscopic factors in the $^{18}O(^3He, d)^{19}F$ reaction provide no real clues. Unfortunately only a limit is known for the lifetime of the 3.91 MeV level [18], but as can be seen from fig. 2 this does rule out an identification with the $K+^{17}O$ $\frac{3}{2}^+_2$ state. The KK calculations could give a reasonable account of the $\gamma$-decays of this level if the lifetime is near the measured limit. Both of these calculations are in marked contrast to the Nilsson model predictions which associate this level with the $K = \frac{3}{2}^+$ band head [11]. A measurement of this lifetime is clearly crucial in choosing between these two models for the level and a third interpretation of the level as an intruder state [6, 14].

The evidence for suggesting this level is an intruder state is circumstantial. The energy predicted for the second $\frac{3}{2}^+$ state is high by at least 1.7 MeV in all known $(sd)^3$ shell model calculations and there are indications that 5p-2h and/or 7p-4h configurations substantially lower the energy of this state [6, 14]. There is also evidence from the $\gamma$-decay of the $T = \frac{3}{2}$ levels (see sect. 5.7) which indicates that the 3907 keV level does not correspond to the $\frac{3}{2}^+_2$ state in the KK or $K+^{17}O$ calculations.

Although the evidence strongly suggests the 3907 keV level in an intruder state, the evidence is even firmer in the case of the 5497 keV $\frac{3}{2}^+$ level. The M1 transitions to the 1554 and 197 keV levels are an order of magnitude larger than predicted by either calculation for the $\frac{3}{2}^+_2$, $\frac{3}{2}^+_3$ or $\frac{3}{2}^+_4$ states. Also this level has a large reduced $\alpha$-width [$\approx 40\,\%$ [ref. [28]]] and decays via relatively strong E1 decays. Neither of these properties is expected for an $(sd)^3$ state and this leads to a possible interpretation of this level as having a significant $p^{-1}(sd)^3(pf)^1$ configuration (see sect. 8).

While the 6498 keV and the 6526 keV $\frac{3}{2}^+$ levels cannot be associated with particular $(sd)^3$ states, there is no evidence to suggest they are not "mostly" $(sd)^3$ in nature since the $(sd)^3$ calculations for the $\frac{3}{2}^+_3$ or $\frac{3}{2}^+_4$ states are capable of explaining the strong transitions which are observed to the ground and 4548 keV levels.

### 5.3. THE $J^\pi = \frac{5}{2}^+$ LEVELS

*5.3.1. The data.* The level at 4548 keV has been isolated from the probable $\frac{3}{2}^-$ level at 4557 keV [ref. [18]] and in conjunction with previous results a firm $J^\pi = \frac{5}{2}^+$ assignment can be made [12, 20, 23]. A study of the 5104 keV level has shown $J = \frac{5}{2}$ [ref. [21]]. Its $\gamma$-decays, as well as the decays of the $T = \frac{3}{2}$ levels [19] to this level, imply that positive parity is likely although particle studies report varying results [23, 24, 29]. Since $\Gamma_\gamma \approx \Gamma_{total}$ for this level [20], its radiative width in the $^{15}N(\alpha, \gamma)^{19}F$ reaction gives its $\alpha$-width. Using a crude estimate of $\omega\gamma$ based on the yield curve in ref. [21]) implies that the reduced $\alpha$-width is $\approx 5\times10^{-4}$. Two studies [23, 24] of the $^{18}O(^3He, d)^{19}F$ reaction have implied $J^\pi = (\frac{5}{2}, \frac{7}{2})^-$ for the 5535 keV level. Although its $\gamma$-decays confirm the $J = \frac{5}{2}$ assignment [21], negative parity would imply a highly unlikely M2 strength of $20\pm7$ W.u. to the ground state. Hence positive parity is preferred but nega-

TABLE 3

Comparison of predicted and observed transition strengths from $J^\pi = \frac{5}{2}^+$ states in $^{19}$F (in W.u.)

| Experiment | | | Theory | | | | |
|---|---|---|---|---|---|---|---|
| | | | | KK | | K+$^{17}$O | |
| transition | M1 | E2 | transition | M1 | E2 | M1 | E2 |
| 197 → 0($\frac{1}{2}^+$) | | 6.42±0.06 | $\frac{5}{2}{}_1^+ \to \frac{1}{2}{}_1^+$ | | 8.0 | | 6.5 |
| 4549 → 0($\frac{1}{2}^+$) | | (< 5 %) | $\frac{5}{2}{}_2^+ \to \frac{1}{2}{}_1^+$ | | 1.12 | | 0.42 |
| → 1554($\frac{3}{2}^+$) | >0.007[a] | | $\to \frac{3}{2}{}_1^+$ | 0.018 | 0.40 | 0.004 | 0.03 |
| → 197($\frac{5}{2}^+$) | >0.010[a] | | $\to \frac{5}{2}{}_1^+$ | 0.006 | 0.41 | 0.020 | 0.05 |
| | | | $\to \frac{9}{2}{}_1^+$ | | 4.3 | | 2.2 |
| 5104 → 197($\frac{5}{2}^+$) | $>2\times10^{-3}$ | | $\frac{5}{2}{}_3^+ \to \frac{1}{2}{}_1^+$ | | 0.23 | | 0.05 |
| | | | $\to \frac{3}{2}{}_1^+$ | 0.011 | 0.16 | 0.002 | $10^{-4}$ |
| 5535 → 0($\frac{1}{2}^+$) | | 0.85±0.25 | $\to \frac{3}{2}{}_2^+$ | 0.10 | 0.04 | 0.15 | 0.58 |
| → 1554($\frac{3}{2}^+$) | <0.012[c] | | $\to \frac{5}{2}{}_1^+$ | 0.017 | 0.03 | 0.024 | 0.009 |
| → 197($\frac{5}{2}^+$) | 0.024±0.008[a] | | $\to \frac{5}{2}{}_2^+$ | 0.59 | 5.9 | 0.28 | 3.9 |
| | | | $\to \frac{9}{2}{}_1^+$ | | 0.35 | | 0.003 |
| 6287 → 1554($\frac{3}{2}^+$) | ≈0.03[b] | | $\frac{5}{2}{}_4^+ \to \frac{1}{2}{}_1^+$ | | 0.63 | | 0.06 |
| | | | $\to \frac{3}{2}{}_1^+$ | 0.001 | 0.009 | 0.013 | 0.06 |
| 6836 → 0($\frac{1}{2}^+$) | | 0.8±0.5 | $\to \frac{3}{2}{}_2^+$ | 0.11 | 1.95 | 0.009 | 0.19 |
| → 197($\frac{5}{2}^+$) | 0.012±0.006 | <1.6 | $\to \frac{5}{2}{}_1^+$ | 0.26 | 0.03 | 0.17 | 0.06 |
| | | | $\to \frac{5}{2}{}_2^+$ | $5\times10^{-4}$ | 0.16 | $3\times10^{-5}$ | 0.07 |
| | | | $\to \frac{7}{2}{}_1^+$ | 0.53 | 2.2 | 0.024 | 0.01 |
| | | | $\to \frac{9}{2}{}_1^+$ | | 2.42 | | 0.48 |

[a]) Assumed pure M1.
[b]) Based on a crude estimate of $\omega\gamma \approx 1$ eV from yield curve in ref. [16]).
[c]) No experimental limit set, an upper limit of 10 % assumed.

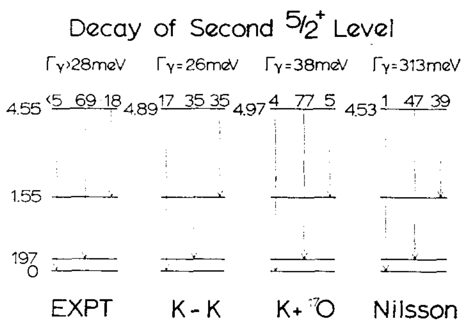


Fig. 3. Comparison of experimental and predicted decay schemes to positive parity levels from the second $\frac{5}{2}^+$ level.

tive parity cannot be ruled out. The level at 6287 keV was assigned $J^\pi = \frac{5}{2}^+$ from an $^{15}$N($\alpha$, $\alpha'$)$^{15}$N study [28]), but due to many other discrepancies found with these assignments [16, 17]) this should be considered as tentative. The 6836 keV level has recently been shown to have $J^\pi = \frac{5}{2}^+$ [ref. [17])].

*5.3.2. Comparison with theory.* (See table 3, figs. 1 and 3.) The decays of the $T = \frac{3}{2}$ states (see sect. 5.7) strongly suggest that the 4548 and 5104 keV levels should be associated with the $\frac{5}{2}{}_2^+$ and $\frac{5}{2}{}_3^+$ states. In the shell model calculations the $\frac{5}{2}{}_2^+$ and $\frac{5}{2}{}_3^+$ states are mixed as shown by the sensitivity to the residual interaction of the calculated spectroscopic factors. In view of this sensitivity and the experimental discrepancies for the spectroscopic factor of the 4548 keV level, the above associations are reasonable, although in the KK case there is some preference for switching the order of the $\frac{5}{2}{}_2^+$ and $\frac{5}{2}{}_3^+$ states. The same conclusions can be drawn by comparing the predicted and observed $\gamma$-decay schemes (fig. 3). In the KK calculations the decay of the nearby $\frac{5}{2}{}_3^+$ state to the 197 keV level is 3 times as strong as from the $\frac{5}{2}{}_2^+$ state and a slight mixing of the states could improve the agreement. The K+$^{17}$O calculations give good agreement while the Nilsson model calculations [11]) predict a substantially different lifetime but somewhat similar decay scheme. As in the case of the 3907 keV level, an accurate lifetime measurement for this level is clearly important.

In general the data are poor for the higher $\frac{5}{2}^+$ levels. The properties of the 5104 keV level are consistent with the above association with the $\frac{5}{2}{}_3^+$ state but the data are not good enough to distinguish between the predictions of the two calculations which are sensitive to the residual interaction. The only notable features of the other $\frac{5}{2}^+$ levels are the E2 transitions to the g.s. which are reasonably explained in the KK calcula-

TABLE 4

Comparison of predicted and observed transition strengths from $J^\pi = \frac{7}{2}^+$ levels in $^{19}$F (in W.u.)

| Experiment | | | Theory | | | | |
|---|---|---|---|---|---|---|---|
| | | | | KK | | K+$^{17}$O | |
| transition | M1 | E2 | transition | M1 | E2 | M1 | E2 |
| 4378 → 1554($\frac{3}{2}^+$) | | (<2 %)[a]) | $\frac{7}{2}{}_1^+ \to \frac{3}{2}{}_1^+$ | | 1.9 | | 6.2 |
| → 197($\frac{5}{2}^+$) | $>1.6\times10^{-2}$ | >0.04 | $\to \frac{5}{2}{}_1^+$ | 0.14 | 0.14 | $10^{-3}$ | 0.52 |
| → 2780($\frac{9}{2}^+$) | $>4.2\times10^{-2}$ | >0.4 | $\to \frac{9}{2}{}_1^+$ | 0.81 | 0.77 | 1.2 | 0.9 |
| 5464 → 1554($\frac{3}{2}^+$) | | 14±4 | $\frac{7}{2}{}_2^+ \to \frac{3}{2}{}_1^+$ | | 5.5 | | 0.7 |
| → 197($\frac{5}{2}^+$) | $(8\pm2)\times10^{-3}$ | <0.2 | $\to \frac{5}{2}{}_1^+$ | $1.4\times10^{-4}$ | 0.04 | 0.12 | 0.21 |
| → 2780($\frac{9}{2}^+$) | 0.9±0.2 | 3±2 | $\to \frac{9}{2}{}_1^+$ | 0.86 | 0.55 | 0.59 | 0.5 |
| → 4378($\frac{7}{2}^+$) | <0.5 | | $\to \frac{7}{2}{}_1^+$ | 0.18 | 0.30 | 0.05 | 0.5 |
| 6070 → 1554($\frac{3}{2}^+$) | | $1.3\pm^{1.6}_{0.7}$ | $\frac{7}{2}{}_3^+ \to \frac{3}{2}{}_1^+$ | | 1.8 | | 0.03 |
| → 197($\frac{5}{2}^+$) | $(8\pm2)\times10^{-2}$ | $1.1\pm^{0.6}_{0.4}$ | $\to \frac{5}{2}{}_1^+$ | $1.5\times10^{-3}$ | 0.60 | 0.03 | 0.31 |
| → 4378($\frac{7}{2}^+$) | 0.27±0.08[b]) | | $\to \frac{7}{2}{}_1^+$ | 0.24 | 1.3 | 0.05 | 0.02 |
| → 2780($\frac{9}{2}^+$) | 0.21±0.05 | | $\to \frac{7}{2}{}_2^+$ | 0.41 | 1.1 | 0.63 | 0.07 |
| | | <3 | $\to \frac{9}{2}{}_1^+$ | 0.54 | 0.12 | 0.02 | 0.03 |
| 6335 → 197($\frac{5}{2}^+$) | ≈0.04[c]) | | $\frac{7}{2}{}_4^+ \to \frac{3}{2}{}_1^+$ | | 0.93 | | 0.07 |
| 6553 → 197($\frac{5}{2}^+$) | $(5\pm1)\times10^{-3}$[d]) | <0.01 | $\to \frac{5}{2}{}_1^+$ | 0.001 | 0.21 | 0.002 | $10^{-5}$ |
| → 2780($\frac{9}{2}^+$) | 0.032±0.008 | <0.3 | $\to \frac{7}{2}{}_1^+$ | 0.05 | 2.2 | 0.003 | 0.04 |
| | | | $\to \frac{7}{2}{}_2^+$ | $3\times10^{-4}$ | 0.18 | 0.07 | 0.22 |
| | | | $\to \frac{9}{2}{}_1^+$ | 0.03 | 0.59 | 0.05 | 0.09 |

[a]) If $\tau$ is chosen to reproduce the M1 transitions in the KK calculation then $|M|_{E2}^2 < 13$ W.u.
[b]) Assumed pure M1 but possible E2 admixtures.
[c]) Based on crude estimate of $\omega\gamma \approx 1$ eV from ref. [16]) yield curves.
[d]) Possibly from an underlying resonance.

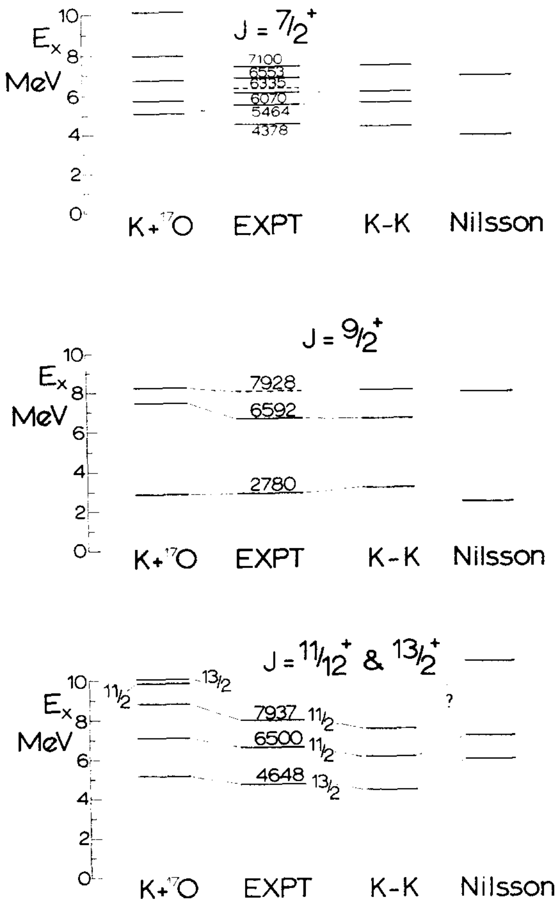


Fig. 4. As in fig. 1 for the $\frac{7}{2}^+$, $\frac{9}{2}^+$, $\frac{11}{2}^+$ and $\frac{13}{2}^+$ levels in $^{19}$F.

tions and the absence of a strong feed to the 197 keV level from a $\frac{5}{2}{}^+_4$ state as predicted in both calculations.

5.4. THE $J^{\pi} = \frac{7}{2}^+$ LEVELS

*5.4.1. The data.* The levels at 4378, 5464 and 6070 keV are firmly established as $\frac{7}{2}^+$ levels [2, 16]. The levels at 6335 and 7100 keV have been assigned $J^{\pi} = \frac{7}{2}^+$ from $^{15}$N($\alpha$, $\alpha'$)$^{15}$N studies [28]) and a sixth $\frac{7}{2}^+$ level has been identified as a possible member of a doublet at 6553 keV. Some very crude estimates of the decay strengths from the 6335 keV level have been made from the yield curve in ref. [21]).

*5.4.2. Comparison with theory.* (See table 4 and fig. 4.) A detailed comparison for the first 3 levels has appeared previously [16]). It was shown that the KK calculations give a good description of the first three $\frac{7}{2}^+$ levels as (sd)$^3$ states while the K+$^{17}$O calculations have several definite shortcomings, including a complete inversion of the first two levels. This inversion in the $K+{}^{17}O$ case, and the good agreement for the KK case are shown in fig. 5.

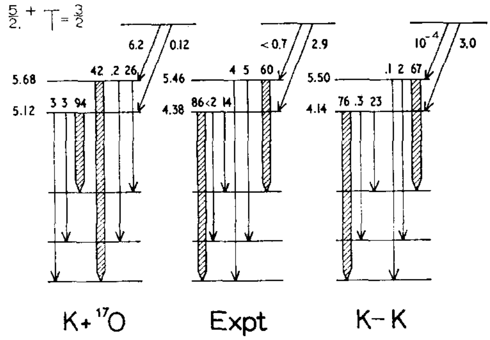


Fig. 5. Decay schemes of the first two experimental and theoretical $\frac{7}{2}^+$ levels to the $197(\frac{5}{2}^+)$, $1554(\frac{3}{2}^+)$ and $2780(\frac{9}{2}^+)$ keV levels. Branching ratios are normalized to experimental totals for the positive parity states. M1 decays from the $T = \frac{3}{2}$ state are shown in W.u.

The data for the other $\frac{7}{2}^+$ levels are not good enough to base any conclusions on; but the data for the 6553 keV level are not inconsistent with the predictions for the $K+{}^{17}O$ $\frac{7}{2}{}_4^+$ state.

An unusual feature of the first three $\frac{7}{2}^+$ levels is that they show a remarkable sensitivity to the residual interaction and at the same time they can be almost completely explained in the $(sd)^3$ shell model. However, there is one marked discrepancy, the large (10 %) reduced $\alpha$-width of the 6.07 MeV level. This cannot be explained by an $(sd)^3$ interpretation, which emphasizes the point made in sect. 2, that large intruder components may be present which do not affect the transition rates.

### 5.5. THE $J^\pi = \frac{9}{2}^+$ LEVELS

*5.5.1. The data.* The level at 7928 keV will tentatively be assigned $J^\pi = \frac{9}{2}^+$ although experimentally $\frac{7}{2}^+$ and $\frac{9}{2}^-$ assignments are also possible [12]).

*5.5.2. Comparison with theory.* (See table 5 and fig. 4.) The eigenvalues and $\gamma$-decay rates predicted by both sets of calculations are in fair agreement with experiment except for the $\frac{9}{2}{}_2^+ \rightarrow \frac{5}{2}{}_1^+$ E2 transition. As is frequently the case, the KK calculations are much closer to experiment which may only reflect the use of Woods-Saxon radial integrals in calculating $B(E2)$ rates.

The decay of the $\frac{9}{2}{}_2^+$ state to the $\frac{7}{2}{}_1^+$ and $\frac{7}{2}{}_2^+$ states is sensitive to the interaction used and cannot be explained by merely exchanging the $\frac{7}{2}^+$ states in the $K+{}^{17}O$ calculations as is usually the case. The agreement obtained for both sets of calculations with experiment is much better than in the Nilsson model calculations which predict the $\frac{9}{2}{}_2^+$ state to be 1.2 MeV too high in energy and predict the $\gamma$-decays to be too weak by a factor of $\approx 5$.

The excitation energy and M1 decay of the 7928 keV level are in good agreement with the $K+{}^{17}O$ calculations for the $\frac{9}{2}{}_3^+$ state, thus justifying the association of the

TABLE 5

Comparison of predicted and observed transition rates from $J^\pi = \frac{9}{2}^+$ levels in $^{19}$F (in W.u.)

| Experiment | | | Theory | | | | |
|---|---|---|---|---|---|---|---|
| | | | | KK | | K+$^{17}$O | |
| transition | M1 | E2 | transition | M1 | E2 | M1 | E2 |
| 2780 → 197($\frac{5}{2}^+$) | | 9.2±1.1 | $\frac{9}{2}{}_1^+ \to \frac{5}{2}{}_1^+$ | | 7.7 | | 6.8 |
| 6592 → 197($\frac{5}{2}^+$) | | 1.6±0.4 | $\frac{9}{2}{}_2 \to \frac{5}{2}{}_1^+$ | | 0.23 | | 0.007 |
| → 4378($\frac{7}{2}^+$) | 0.35±0.08 | <6 | $\to \frac{7}{2}{}_1^+$ | 0.25 | 3.3 | 0.61 | 0.86 |
| → 5464($\frac{7}{2}^+$) | <0.9 | | $\to \frac{7}{2}{}_2^+$ | 0.03 | 1.6 | 0.32 | 2.75 |
| → 2780($\frac{9}{2}^+$) | 0.17±0.05 | <20 | $\to \frac{9}{2}{}_1^+$ | 0.19 | 0.16 | 0.23 | 0.23 |
| 7928 → 197($\frac{5}{2}^+$) | | 0.25±0.09 | $\frac{9}{2}{}_3^+ \to \frac{5}{2}{}_1^+$ | | | | 0.012 |
| → 2780($\frac{9}{2}^+$) | 0.15±0.04[a]) | | $\to \frac{7}{2}{}_1^+$ | | | 0.004 | 0.03 |
| | | | $\to \frac{7}{2}{}_2^+$ | | | 0.024 | 0.02 |
| | | | $\to \frac{9}{2}{}_1^+$ | | | 0.10 | 0.02 |
| | | | $\to \frac{13}{2}{}_1^+$ | | | | 1.2 |

[a]) Assumed pure M1.

level with the $\frac{9}{2}{}_3^+$ state. It is unfortunate that the KK calculations were not done for this state since it would be interesting to see if they could account for the E2 strength to the $\frac{5}{2}{}_1^+$ state which is missing from the K+$^{17}$O calculations.

### 5.6. THE $J^\pi = \frac{11}{2}^+$ AND $\frac{13}{2}^+$ LEVELS

*Comparison with theory.* (See table 6, fig. 4.) Both sets of calculations give a reasonable account of the excitation energies of the two known $\frac{11}{2}^+$ levels and the

TABLE 6

Comparison of the predicted and observed transition rates from $J^\pi = \frac{11}{2}^+$ and $\frac{13}{2}^+$ levels in $^{19}$F (in W.u.)

| Experiment | | | Theory | | | | |
|---|---|---|---|---|---|---|---|
| | | | | KK | | K+$^{17}$O | |
| transition | M1 | E2 | transition | M1 | E2 | M1 | E2 |
| 6500 → 4378($\frac{7}{2}^+$) | | <100 | $\frac{11}{2}{}_1^+ \to \frac{7}{2}{}_1^+$ | | 4.3 | | 0.15 |
| | | | $\to \frac{7}{2}{}_2^+$ | | 0.25 | | 1.69 |
| → 2780($\frac{9}{2}^+$) | 0.19±0.03 | <0.24 | $\to \frac{9}{2}{}_1^+$ | 0.15 | 0.03 | 0.095 | 0.013 |
| → 4648($\frac{13}{2}^+$) | 1.4±0.3 | <14 | $\to \frac{13}{2}{}_1^+$ [a]) | 0.84 | 1.97 | 0.18 | 1.03 |
| 7937 → 4378($\frac{7}{2}^+$) | | <19 | $\frac{11}{2}{}_2^+ \to \frac{7}{2}{}_1^+$ | | 0.003 | | 3.3 |
| → 2780($\frac{9}{2}^+$) | 0.020±0.006[a]) | | $\to \frac{7}{2}{}_2^+$ | | 4.4 | | 0.51 |
| | | | $\to \frac{9}{2}{}_1^+$ | 0.002 | 0.04 | 0.017 | 0.11 |
| → 4648($\frac{13}{2}^+$) | 0.63±0.12 | <3 | $\to \frac{13}{2}{}_1^+$ | 1.08 | 0.04 | 1.64 | 0.014 |
| | | | $\frac{11}{2}{}_3^+ \to \frac{7}{2}{}_1^+$ | | $8\times10^{-4}$ | | 1.9 |
| | | | $\to \frac{9}{2}{}_1^+$ | 0.01 | 0.007 | 0.005 | 0.09 |
| | | | $\to \frac{13}{2}{}_1^+$ | 0.33 | 0.53 | 0.04 | 0.9 |
| 4648 → 2780($\frac{9}{2}^+$) | | 5.8±0.7 | $\frac{13}{2}{}_1^+ \to \frac{9}{2}{}_1^+$ | | 5.3 | | 4.7 |

[a]) Assumed pure M1.

TABLE 7

Comparison of predicted and observed transition rates from the $T = \frac{3}{2}$ levels in $^{19}$F (in W.u.)

| Experiment | | | Theory | | | | |
|---|---|---|---|---|---|---|---|
| | | | | KK | | K+$^{17}$O | |
| transition | M1 | E2 | transition | M1 | E2 | M1 | E2 |
| $7540(\frac{5}{2}^+) \rightarrow 1554(\frac{3}{2}^+)$ | $0.44 \pm 0.08$ | $<0.15$ | $\frac{5}{2}^+ \rightarrow \frac{1}{2}{}_1^+$ | | 0.19 | | 0.04 |
| $\rightarrow 3907(\frac{3}{2}^+)$ | $<0.05$ | | $\rightarrow \frac{3}{2}{}_1^+$ | 0.60 | 0.03 | 0.25 | 0.003 |
| $\rightarrow 197(\frac{5}{2}^+)$ | $0.17 \pm 0.04$ | $0.29^{+0.17}_{-0.06}$ | $\rightarrow \frac{3}{2}{}_2^+$ | 0.02 | 0.09 | 0.26 | 0.05 |
| $\rightarrow 4548(\frac{5}{2}^+)$ | $<0.2$ | | $\rightarrow \frac{3}{2}{}_3^+$ | 0.48 | 0.07 | 0.014 | 0.06 |
| $\rightarrow 5104(\frac{5}{2}^+)$ | $0.5 \pm 0.3$ [a] | | $\rightarrow \frac{5}{2}{}_1^+$ | 0.072 | 0.33 | 0.075 | 0.19 |
| $\rightarrow 4378(\frac{7}{2}^+)$ | $2.9 \pm 0.8$ | $<140$ | $\rightarrow \frac{5}{2}{}_2^+$ | 0.15 | 0.10 | $9 \times 10^{-4}$ | 0.14 |
| $\rightarrow 5464(\frac{7}{2}^+)$ | $<0.7$ | | $\rightarrow \frac{5}{2}{}_3^+$ | 1.24 | 0.43 | 0.28 | 0.003 |
| | | | $\rightarrow \frac{7}{2}{}_1^+$ | 2.96 | 0.49 | 0.12 | 0.22 |
| | | | $\rightarrow \frac{7}{2}{}_2^+$ | $10^{-4}$ | 0.19 | 6.2 | 0.34 |
| | | | $\rightarrow \frac{9}{2}{}_1^+$ | | 0.75 | | 0.25 |
| $7657(\frac{3}{2}^+) \rightarrow 0(\frac{1}{2}^+)$ | $0.16 \pm 0.05$ | $<0.16$ | $\frac{3}{2}^+ \rightarrow \frac{1}{2}{}_1^+$ | 0.21 | 0.07 | 0.15 | 0.05 |
| $\rightarrow 1554(\frac{3}{2}^+)$ | $0.40 \pm 0.13$ | $<0.3$ | $\rightarrow \frac{1}{2}{}_2^+$ | 0.09 | 0.02 | 0.03 | 0.008 |
| $\rightarrow 3907(\frac{3}{2}^+)$ | $<0.1$ | | $\rightarrow \frac{3}{2}{}_1^+$ | 0.36 | 0.10 | 0.16 | 0.08 |
| $\rightarrow 197(\frac{5}{2}^+)$ | $0.084 \pm 0.028$ | $0.24^{+0.40}_{-0.20}$ | $\rightarrow \frac{3}{2}{}_2^+$ | 0.31 | 0.16 | 0.003 | 0.44 |
| $\rightarrow 4548(\frac{5}{2}^+)$ | $0.57 \pm 0.28$ [a] | | $\rightarrow \frac{3}{2}{}_3^+$ | 0.06 | 1.94 | 0.67 | 0.06 |
| $\rightarrow 5104(\frac{5}{2}^+)$ | $1.9 \pm 0.8$ [a] | | $\rightarrow \frac{3}{2}{}_4^+$ | 0.62 | 0.003 | 0.47 | 0.03 |
| | | | $\rightarrow \frac{5}{2}{}_1^+$ | 0.045 | 0.95 | 0.012 | 0.38 |
| | | | $\rightarrow \frac{5}{2}{}_2^+$ | 0.64 | 0.001 | 0.33 | 0.85 |
| | | | $\rightarrow \frac{5}{2}{}_3^+$ | 1.58 | 0.02 | 2.12 | 0.004 |
| | | | $\rightarrow \frac{7}{2}{}_1^+$ | | 0.25 | | 0.07 |
| | | | $\rightarrow \frac{7}{2}{}_2^+$ | | 0.68 | | 0.03 |
| $8.79(\frac{1}{2}^+) \rightarrow 0(\frac{1}{2}^+)$ | $(5 \pm 3) \times 10^{-4}$ | | $\frac{1}{2}^+ \rightarrow \frac{1}{2}{}_1^+$ | | | $12 \times 10^{-4}$ | |
| $\rightarrow 5938(\frac{1}{2}^+)$ | $0.020 \pm 0.012$ [a] | | $\rightarrow \frac{1}{2}{}_2^+$ | | | 0.43 | |
| $\rightarrow 1554(\frac{3}{2}^+)$ | $(5 \pm 2) \times 10^{-3}$ [a] | | $\rightarrow \frac{3}{2}{}_1^+$ | | | 0.021 | $6 \times 10^{-5}$ |
| $\rightarrow 3907(\frac{3}{2}^+)$ | $0.04 \pm 0.01$ [a] | | $\rightarrow \frac{3}{2}{}_2^+$ | | | 0.48 | 0.78 |
| $\rightarrow 6498(\frac{3}{2}^+)$ | $0.08 \pm 0.04$ [a] | | $\rightarrow \frac{3}{2}{}_3^+$ | | | 3.4 | 0.04 |
| $\rightarrow 6526(\frac{3}{2}^+)$ | $0.020 \pm 0.014$ [a] | | $\rightarrow \frac{3}{2}{}_4^+$ | | | 0.80 | 0.29 |
| $\rightarrow 197(\frac{5}{2}^+)$ | | $0.16 \pm 0.09$ | $\rightarrow \frac{5}{2}{}_1^+$ | | | | 0.46 |

[a]) Assumed pure M1.

$\frac{13}{2}^+$ level. The mixing of the $\frac{11}{2}^+$ states predicted in ref. [5]) is evidenced here by the sensitivity of the predicted decay strengths to the $\frac{13}{2}^+$ state. This is similar to, but not as simple as the mixing of the $\frac{7}{2}^+$ states noted above. In this case of mixing, there is also a clear preference for the KK description on the basis of the experimentally observed M1 strengths to the $\frac{13}{2}^+$ level.

5.7. THE $T = \frac{3}{2}$ STATES

*5.7.1. The data.* The results of a preliminary study of the weak feeds from the first two $T = \frac{3}{2}^+$ levels in $^{19}$F using the $^{15}$N$(\alpha, \gamma)^{19}$F reaction are given in table 7 [ref. [19])]. The branching ratios for the decay of the tentative $T = \frac{3}{2}$ $J^\pi = \frac{1}{2}^+$ level at 8.79 MeV are from ref. [27]) and are in reasonable agreement with the results of ref. [20]) except that several new weak feeds are reported. The absolute width is taken from ref. [20]). The strengths of the weak feeds from the $J^\pi = \frac{1}{2}^+$ level should be considered as upper limits since the width of the resonance (40 keV) made it difficult to establish their resonant character in the $^{18}$O(p, $\gamma$)$^{19}$F reaction.

*5.7.2. Comparison with theory.* (See table 7.) The strong feeds from the $\frac{5}{2}^+$ and $\frac{3}{2}^+$ $T = \frac{3}{2}$ levels are well explained by the KK calculations while the K+$^{17}$O calculations give reasonable agreement if the first two $\frac{7}{2}^+$ states are interchanged (as is consistent with the data on these states). The experimental data are not yet good enough to distinguish between the calculations where the predictions are markedly different (e.g. the $\frac{5}{2}^+ \rightarrow \frac{5}{2}^+_3$ transition). The feeds to the 4548 and 5104 keV $\frac{5}{2}^+$ levels support their interpretation as the $\frac{5}{2}^+_2$ and $\frac{5}{2}^+_3$ states in both calculations. Although there is some evidence from the data on these levels (see subsect. 5.3) that there is some inversion of these states in the KK calculations, this is not evidenced here.

The agreement of theory and experiment for the $\frac{1}{2}^+$ level at 8.79 MeV is not good overall although theory qualitatively accounts for the relatively strong transitions to the 197, 6498 and 6526 keV levels. The lack of quantitative agreement may reflect the difficulty in extracting the $\gamma$-decay width from the data or possible isospin mixing of the level with underlying $T = \frac{1}{2}$ states.

Taken together, the observed decays and limits on decays to the 3907 keV $\frac{3}{2}^+$ level from the $T = \frac{3}{2}$ levels give a clear indication that it is not the $\frac{3}{2}^+_2$ state in either calculation. It is worth noting the extreme sensitivity to the residual interaction of the predicted strengths to all the excited $\frac{3}{2}^+$ states.

## 6. The E1 selection rule in $^{19}$F

It has been shown [30,56]) that the E1 operator cannot connect an $n$-particle state with a state considered as a single neutron or proton hole coupled to an $(n+1)$-particle core. As a direct consequence E1 transitions between positive parity (sd)$^3$ states and negative parity p$^{-1}$(sd, $T = 0$)$^4$ states in $^{19}$F are forbidden although E1 transitions to and from p$^{-1}$(sd, $T = 1$)$^4$ configurations [which have been included in ref. [31]) in a description of the negative parity states of $^{19}$F] are not forbidden by this rule since the hole state must include both neutron and proton components to give a state of good isospin in $^{19}$F. Thus the observed E1 transitions in $^{19}$F indicate breakdowns for one or two reasons: (i) there are 5p-2h or p$^{-1}$(sd)$^3$(fp) components in the positive parity states; or (ii) there are p$^{-1}$(sd, $T = 1$)$^4$ or (sd)$^2$(fp)$^1$ components in the negative parity states.

The E1 decays from members of the $K = \frac{1}{2}^-$ negative parity band in $^{19}$F (thought to be mostly p$^{-1}$(sd, $T = 0$)$^4$ in nature) indicate this rule is valid to the extent that all observed E1 strengths are $\leqq 1.3 \times 10^{-3}$ W.u. [ref. [32])]. From table 8 it can be seen that E1 transitions from states thought to be (sd)$^3$ are all $\lessapprox 5 \times 10^{-3}$ W.u. while states thought to have an intruder character (*viz.* the 5336 and 5497 keV levels and partially the 5938 keV level) show the strongest E1 decays in $^{19}$F. Thus the E1 selection rule is qualitatively in agreement with the assessment of the natures of these levels

TABLE 8

E1 transition strengths from positive parity states in $^{19}$F (in W.u. $\times 10^3$)

| Initial state \ Final state | $110(\frac{1}{2}^-)$ | $1346(\frac{5}{2}^-)$ | $1459(\frac{3}{2}^-)$ | $3999(\frac{7}{2}^-)$ | $4032(\frac{9}{2}^-)$ |
|---|---|---|---|---|---|
| $1554(\frac{3}{2}^+)$ | $5.4 \pm 2.7$ | | | | |
| $3907(\frac{3}{2}^+)$ | $>1.7$ | ($<4$ %) | ($<4$ %) | | |
| $4378(\frac{7}{2}^+)$ | | ($<2$ %) | | | |
| $4548(\frac{5}{2}^+)$ | | $>0.04$ | $>0.1$ | | |
| $5104(\frac{5}{2}^+)$ | | | $>0.05$ | | |
| $5336(\frac{1}{2}^+)$ | $10 \pm 1.5$ | | $12 \pm 2$ | | |
| $5464(\frac{7}{2}^+)$ | | $6 \pm 1$ | | | |
| $5497(\frac{3}{2}^+)$ | $5 \pm 1.5$ | $15 \pm 5$ | | | |
| $5535(\frac{5}{2}^+)$ | | | $2.3 \pm 0.8$ | | |
| $5938(\frac{1}{2}^+)$ | $1.1 \pm 0.5$ | | $8 \pm 3$ | | |
| $6070(\frac{7}{2}^+)$ | | $2.5 \pm 0.6$ | | $<3$ | $<1.5$ |
| $6498(\frac{3}{2}^+)$ | $0.9 \pm 0.2$ | $1.8 \pm 0.4$ | $3.4 \pm 0.7$ | | |
| $6500(\frac{11}{2}^+)$ | | | | | $<3$ |
| $6526(\frac{3}{2}^+)$ | $5.4 \pm 0.9$ | | | | |
| $6553(\frac{7}{2}^+)$ | | $1.1 \pm 0.3$ | | | |
| $6592(\frac{9}{2}^+)$ | | | | $<1.6$ | $<0.9$ |
| $6836(\frac{5}{2}^+)$ | | | $2.0 \pm 0.4$ | | |
| $7540(\frac{5}{2}^+)$ } $T = \frac{3}{2}$ | | $<0.5$ | $<0.3$ | | |
| $7657(\frac{3}{2}^+)$ } $T = \frac{3}{2}$ | $<0.3$ | $<0.2$ | $<0.2$ | | |
| $8.79(\frac{1}{2}^+)$ } $T = \frac{3}{2}$ | $0.40 \pm 0.10$ | | $0.55 \pm 0.15$ | | |
| $7937(\frac{11}{2}^+)$ | | | | | $<3$ |

given above on the basis of their inexplicable M1 strengths. Hopefully a better understanding of the details of the structure and a proper handling of the spurious centre-of-mass motion may lead to a quantitative analysis of the E1 decays.

## 7. The "$K = \frac{3}{2}^+$ band" with $K = \frac{5}{2}^+$?

As shown above, the $(sd)^3$ shell model provides a third alternative to the $K = \frac{3}{2}^+$ band hypotheses suggested by Dixon *et al.* [12]) and by Garrett and Hansen [11]). If one accepts the hypothesis that the levels in this "band" are $(sd)^3$ states (except for the intruder at 3907 keV) then this is note merely a description which is equivalent to the Nilsson model $K = \frac{3}{2}^+$ band interpretation. It was shown in ref. [33]) that the $\frac{5}{2}^+_2$, $\frac{7}{2}^+_2$ and $\frac{9}{2}^+_2$ states in their $(sd)^3$ shell model calculation can be associated with a $K = \frac{5}{2}^+$ intrinsic state with negative deformation based on Nilsson orbit 5. Orthogonality requirements imply that these states are mixed with those based on the $K = \frac{1}{2}^+$ intrinsic state and in fact mixing was strongest for the $\frac{7}{2}^+$ and $\frac{11}{2}^+$ states. As shown here this mixing is very sensitive to the residual interaction used in the shell model calculation, which may modify some of the conclusions of ref. [33]) slightly. Nonetheless this interpretation of the $\{J^\pi_2\}$ states in the $(sd)^3$ calculation implies they are not equivalent to the Nilsson model interpretation of ref. [11]).

Experimentally the evidence does not yet provide a definitive choice among the alternatives but there is a strong preference for the shell model interpretation since it gives more satisfactory energy eigenvalues for the first two $\frac{7}{2}^+$, $\frac{9}{2}^+$ and $\frac{11}{2}^+$ levels. Overall it also reproduces the $\gamma$-decay strengths more reasonably and is notably more successful in describing the decay of the 6592 keV $\frac{9}{2}^+$ level. However, the crucial test will be an accurate measurement of the lifetimes of the 3907 and 4548 keV levels.

## 8. Another possible band

The 5336 and 5497 keV levels have been shown to be intruder states. On account of the large reduced $\alpha$-widths of these levels and their energies, it has been suggested [refs. [34, 16]] that they consist of a $p_{\frac{1}{2}}$ hole coupled to the $1^-$ level at 5.79 MeV in $^{20}$Ne, which also has a large reduced $\alpha$-width. Although their $\gamma$-decay strengths have not been measured, the $\frac{5}{2}^+$ and $\frac{7}{2}^+$ levels at 6.29 and 7.10 MeV in $^{19}$F have also been suggested [17]) as possible members of this band formed by coupling a $p_{\frac{1}{2}}$ hole to the $3^-$ level at 7.17 MeV in $^{20}$Ne.

The $1^-$ level at 5.79 MeV is strongly populated with an $l = 1$ transfer in the $^{19}$F ($^3$He, d)$^{20}$Ne reaction [2]) which implies that it has a large $(sd)^3(fp)^1$ component (although requirements on the centre of mass motion imply $p^{-1}(sd)^5$ components must also be present [13])). The above model for the levels in $^{19}$F then implies that they have a significant $p^{-1}(sd)^3(pf)^1$ component which may explain the large M1 decay strengths to $(sd)^3$ states which are forbidden from 5p-2h intruder states. It also may explain the relatively large E1 strengths.

## 9. Three particle transfer reactions

In several recent papers [10, 35, 36]) the usefulness of the $^{16}$O($^6$Li, t)$^{19}$Ne and $^{16}$O($^6$Li, $^3$He)$^{19}$F three particle transfer reactions has been demonstrated. With our present understanding of the reaction mechanisms involved, detailed quantitative comparisons are not yet feasible. However, making a few simplifying assumptions allows qualitative comparisons to be made which can also demonstrate the sensitivity of the predictions of the $(sd)^3$ shell model to the residual interaction used. If it is assumed that the reactions are direct and the transferred particles are in a relative S state, then in SU(3) terms, these reactions can proceed only through the components of the (6, 0) representation in the final-state wave function. Thus the spectroscopic factors deduced for three particle transfer tell us the relative strength of the (6, 0) representation in each state. Table 9 contains the amplitudes of the (6, 0) configuration in the $(sd)^3$ shell model states [13]) for the $T = \frac{1}{2}$ mass-19 systems using the KK and K+$^{17}$O residual interactions as well as the same calculations using the matrix elements of Kuo and Brown [37]). This table clearly demonstrates the sensitivity of the wave functions to the residual interaction used. In particular the $\frac{7}{2}^+$, $\frac{11}{2}^+$ and $\frac{3}{2}^+$ states are sensitive as has been shown from a study of their $\gamma$-decays. Qualitatively these calculations demonstrate that the three particle transfer reactions can be a powerful tool. For example the observed ratio of spectroscopic factors to the first two $\frac{5}{2}^+$ levels in $^{19}$F is $\lesssim 0.19$ [ref. [35]]] in rough agreement with the predicted ratio of (6, 0) components in these states for all three calculations. Furthermore the 5.10 MeV

TABLE 9

The amplitudes of the SU(3) (6, 0) representation in $(sd)^3$ shell model states (in %)

| State | KK | K+$^{17}$O | Kuo-Brown |
|---|---|---|---|
| $\frac{1}{2}_1$ | 89 | 86 | 88 |
| $\frac{1}{2}_2$ | 2 | 8 | 4 |
| $\frac{1}{2}_3$ | 0.8 | 0.2 | 0.1 |
| $\frac{3}{2}_1$ | 63 | 73 | 72 |
| $\frac{3}{2}_2$ | 0.2 | 12 | 11 |
| $\frac{3}{2}_3$ | 21 | 0.02 | 1.6 |
| $\frac{5}{2}_1$ | 69 | 75 | 72 |
| $\frac{5}{2}_2$ | 16 | 13 | 14 |
| $\frac{5}{2}_3$ | 5 | 4 | 3 |
| $\frac{5}{2}_4$ | 0.5 | 0.4 | 1.8 |
| $\frac{7}{2}_1$ | 10 | 68 | 3 |
| $\frac{7}{2}_2$ | 34 | 8 | 64 |
| $\frac{7}{2}_3$ | 17 | 0.02 | 0.9 |
| $\frac{7}{2}_4$ | 11 | 1 | 8 |
| $\frac{9}{2}_1$ | 74 | 81 | 75 |
| $\frac{9}{2}_2$ | 8 | 8 | 10 |
| $\frac{9}{2}_3$ | 0.7 | 0.03 | 0.3 |
| $\frac{9}{2}_4$ | 13 | 8 | 10 |
| $\frac{11}{2}_1$ | 5 | 0.1 | 0.2 |
| $\frac{11}{2}_2$ | 14 | 40 | 20 |
| $\frac{11}{2}_3$ | 51 | 34 | 53 |
| $\frac{13}{2}_1$ | 58 | 70 | 64 |
| $\frac{13}{2}_2$ | 41 | 30 | 36 |

level is also observed in this reaction with a peak cross section $\approx \frac{1}{3}$ that of the 4.55 MeV level, in agreement with the identification of this level as the $\frac{5}{2}^+_3$ state and the predicted (6, 0) component in this state. In the case of the $\frac{7}{2}^+$ levels, the 4.38 MeV level has a spectroscopic factor $\approx \frac{1}{10}$ that of the 5.46 MeV level. As was the case with the $\gamma$-decay rates, this is better explained by the KK calculations than the K+$^{17}$O calculations and even better agreement is obtained for the Kuo-Brown matrix elements (or the K+$^{17}$O calculations if the states are inverted). The non-observation of the $\frac{11}{2}^+$ at 6.50 MeV is also in qualitative agreement with the calculations as is the observation of a weak group to the possible second $\frac{11}{2}^+$ at 7.91 MeV in $^{19}$Ne [ref. [36])] (cf. the analogue at 7.94 MeV in $^{19}$F). On the basis of the KK calculations one can speculate that the large peaks at 8.70 and 9.38 MeV in the $^{16}$O($^6$Li, t)$^{19}$Ne spectra [ref. [36])] are the $\frac{13}{2}_2$ and $\frac{11}{2}_3$ states which are expected to have large (6, 0) components and lie at 8.42 and 9.53 MeV respectively.

## 10. Conclusions

It has been shown that over 16 levels in $^{19}$F can be explained in terms of the $(sd)^3$ shell model without introducing more configurations, although the observed sensitivity of the calculations to the residual interaction does leave an ambiguity. The case of the $\frac{3}{2}^+$ states illustrates this ambiguity well. It is more than just coincidence that there are two low-lying $\frac{3}{2}^+$ intruder levels and that the shell model calculations are sensitive to the residual interaction used in the calculations. This sensitivity is probably due to the fact that the K+$^{17}$O matrix elements are renormalized using perturbation theory to account for 1p-1h and 2p-2h excitations. Since the $\frac{3}{2}^+$ level at 5.50 MeV is thought to have a significant $p^{-1}(sd)^3(pf)^1$ component as well as a $p^{-2}(sd)^5$ component, it is not surprising that the $(sd)^3$ calculations should be sensitive to the presence of the intruder states via the 1p-1h or 2p-2h renormalization terms. Moreover, the fact that these levels lie so low in excitation implies perturbation theory is not likely to be a valid approach for renormalizing the matrix elements.

Despite the complications discussed above, the $\gamma$-decay data on $^{19}$F provide a very stringent test of any shell model calculations, either including p-h excitations or not. These data can be used to restrict the possible alternatives used to explain the known

TABLE 10

Summary of transition rates in $^{19}$F which are critical tests of models [a])

| Transition | | Reasons for importance | | |
|---|---|---|---|---|
| | | one level appears to be an intruder | matrix element is large | predicted transition rate is sensitive to residual interaction used |
| $5.34(\frac{1}{2})$ | $\rightarrow 0(\frac{1}{2})$ | × | × | |
| $5.94(\frac{1}{2})$ | $\rightarrow 3.91(\frac{3}{2})$ | × | × | × |
| | $\rightarrow 197(\frac{5}{2})$ | × | × | × |
| $5.50(\frac{3}{2})$ | $\rightarrow 1.55(\frac{3}{2})$ | × | × | |
| | $\rightarrow 197(\frac{5}{2})$ | × | × | |
| $6.53(\frac{3}{2})$ | $\rightarrow 0(\frac{1}{2})$E2 | | × | × |
| | $\rightarrow 4.55(\frac{5}{2})$ | | × | |
| $5.54(\frac{5}{2})$ | $\rightarrow 0(\frac{1}{2})$ | | × | × |
| $6.07(\frac{7}{2})$ | $\rightarrow 4.38(\frac{7}{2})$ | | × | × |
| | $\rightarrow 2.78(\frac{9}{2})$ | | × | × |
| $6.59(\frac{9}{2})$ | $\rightarrow 197(\frac{5}{2})$ | | × | |
| $7.93(\frac{9}{2})$ | $\rightarrow 197(\frac{5}{2})$ | | × | |
| | $\rightarrow 2.78(\frac{9}{2})$ | | × | |
| $7.54(\frac{5}{2}, \frac{3}{2})$ | $\rightarrow 5.10(\frac{5}{2})$ | | × | × |
| $7.66(\frac{3}{2}, \frac{3}{2})$ | $\rightarrow 3.91(\frac{3}{2})$ | × | | × |
| | $\rightarrow 4.55(\frac{5}{2})$ | | × | × |
| | $\rightarrow 5.10(\frac{5}{2})$ | | × | × |

[a]) Transitions from the first two levels of each spin are also included in this category.

intruder states. For these purposes some of the data are more important than others. The properties of the first two levels of each spin are naturally of interest. As well as these, all large transition strengths (M1 $\gtrapprox$ 0.3 W.u., E2 $\gtrapprox$ 1 W.u.) are of importance since they imply significant amounts of common configurations in the states involved (e.g. the relatively strong decay of the 5938 keV $\frac{1}{2}^+$ level to the 3907 keV $\frac{3}{2}^+$ level implies that if the 3907 keV level is 7p-4h or 5p-2h, then the 5938 keV level has significant deformed components as well). In addition some decays are of interest since the predicted rates are sensitive to the interaction used. Finally, some transitions are of interest since one of the levels involved is not explained in any known $(sd)^3$ calculations indicating that they are intruder states. Table 10 contains a summary of the transitions falling into these categories.

## 11. Summary

It has been shown that the $(sd)^3$ shell model gives a reasonable explanation of the known properties of the $\frac{5}{2}{}^+_2$ through $\frac{11}{2}{}^+_2$ levels in $^{19}$F with a preference for using the Kallio-Kolltveit residual interaction. On account of several definite shortcomings it is unlikely that the Nilsson model interpretation of the "$K = \frac{3}{2}^+$ band" is valid. In light of ref. [33]) the $\{J^\pi_2\}$ levels may correspond to a $K = \frac{5}{2}^+$ band with negative deformation which is mixed with the ground state band.

The levels at 3907, 5336 and 5497 keV have been shown to be "intruder states" and it appears likely that 5p-2h, 7p-4h and $p^{-1}(sd)^3(fp)^1$ configurations will all play a role in their structure. In particular the simple model of the 5336 and 5497 keV levels as a $p_{\frac{1}{2}}$ hole coupled to the $1^-$ state in $^{20}$Ne implies that the $p^{-1}(sd)^3(pf)^1$ configurations are of importance.

Finally, the good or partial agreement obtained for 15 to 20 positive parity states in $^{19}$F is a remarkable success for the $(sd)^3$ shell model, and more importantly, this agreement should provide a solid base from which we can extend our understanding of p-h excitations.

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