where the choice of $+$ or $-$ represents either outgoing or incoming boundary conditions on the distorted waves. k is the wave number of the relative motion of the target and projectile, μ is the reduced mass, and V_c is the Coulomb potential produced by a uniform spherical charge distribution of radius

$$R_c=r_cA^{1/3}, \tag{A2}$$

where A is the atomic weight of the target.

The optical potentials in (A1) are defined by

$$U=-V/(1+e^x)-iW/(1+e^{x'}), \tag{A3}$$

where

$$x=(r-r_0A^{1/3})/a \tag{A4}$$

and

$$x'=(r-r_0'A^{1/3})/a'. \tag{A5}$$

U_s is given by

$$U_s=-2(V_s+iW_s)\frac{1}{r}\frac{d}{dr}\left(\frac{1}{1+e^x}\right). \tag{A6}$$

The parameters used in the calculation presented here were $V=22.1$ MeV, $W=15.9$ MeV, $W_s=0$ MeV, $V_s=4.31$ MeV, $W_s=-0.11$ MeV, $r_0=0.902$ F, $a=0.452$ F, $r_0'=1.19$ F, $a'=0.556$ F, and $r_c=1.33$ F. For the present calculations Eq. (A1) was solved in a manner appropriate to the evaluation of Eq. (1) using an adaptation of the Oak Ridge code JULIE due to R. M. Drisko.

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Levels of F^{18} from the $O^{16}(He^3,p\gamma)F^{18}$ Reaction*

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Angular correlations in the $O^{16}(He^3,p\gamma)F^{18}$ reaction have been studied through two-parameter analyses of proton–gamma-ray coincidences at He^3 bombarding energies of 4.65, 5.40, and 6.40 MeV. Protons were detected by an annular solid-state detector centered at $\theta_p=180°$; gamma rays were detected with a NaI(Tl) spectrometer for five angles in the range $0°\leq\theta_\gamma\leq90°$. Branching ratios were determined for nine of the ten F^{18} levels of $3.4<E_{ex}<4.9$ MeV; the exception is the 4.74-MeV level, which was not observed. From analysis of angular-correlation data the following spin-parity limitations are obtained for the triplet of levels at $E_{ex}\sim3.8$ MeV: 3.72-MeV level ($J=1$); 3.79-MeV level ($J=1$, 2, or 3); and 3.84-MeV level ($J^\pi=2^{(+)}$). The preference for an even-parity assignment for the 3.84-MeV level is quite strong. The decay modes of the 3.79-MeV level are consistent with the assumption that this is the 3^- member of the group of odd-parity levels which includes those at 1.08 MeV (0^-), 2.10 MeV (2^-), and 3.13 MeV (expected 1^-). For those levels with $E_{ex}>4$ MeV, the correlation analysis provides restrictions on possible level spins and on multipole-mixing amplitudes for some of the principal deexcitation transitions. These results are consistent with other available information. The 4.65-MeV level of F^{18} is found to have $J\geqslant3$, and decays by transitions to the 0.94-MeV level ($J^\pi=3^+$) and to the 1.13-MeV level [$J^\pi=(5)^+$] with branching ratios of 15 and 85%, respectively. This appears to be the most likely candidate for the $J^\pi=4^+$, $T=1$ analog of the 3.55-MeV 4^+ state of O^{18}. The F^{18} 4.40-MeV level is also observed to decay to the 1.13-MeV level, and is a possible but less likely candidate for the analog of this O^{18} level.

I. INTRODUCTION

In a recent publication[1] we reported an investigation of the first 10 excited states of F^{18} ($E_{ex}<3.4$ MeV) from the $O^{16}(He^3,p\gamma)F^{18}$ reaction ($Q=2.021$ MeV). In the present paper we report an extension of these measurements into the range of excitation $3.4<E_{ex}<4.9$ MeV. For convenience, previously available[1–9] information on the F^{18} level structure is summarized in Fig. 1 for levels of $E_{ex}<4.9$ MeV. Excitation energies and branching ratios for those levels of $E_{ex}<4$ MeV are those summarized in a recent report[9] of high-resolution Ge(Li) studies of F^{18} gamma rays, and incorporate the earlier results of Refs. 1–8. The position of those levels of $E_{ex}>4$ MeV are taken primarily from the compilation of Ajzenberg-Selove and Lauritsen,[2] but include some results from the present work. Indicated spin assignments are from the information presented, or reviewed, in Refs. 1–9. We note in particular that the $J=0$ assignment for the 1.08-MeV level is from the results of

* Work performed under the auspices of the U. S. Atomic Energy Commission.

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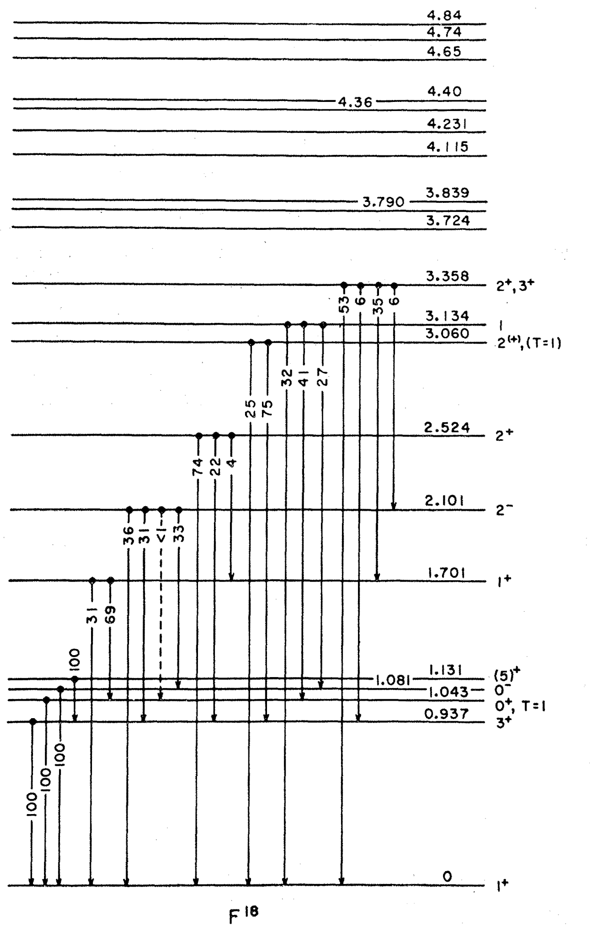

FIG. 1. Summary of previously available information on the levels of F^{18} of excitation energy $E_{ex}<4.9$ MeV. Branching ratios and spin-parity assignments given for levels of $E_{ex}<3.4$ MeV are from the information summarized in the text; the levels of $E_{ex}>3.4$ MeV are the subject of the present investigation.

Chagnon[6] and Gorodetzky *et al.*,[7] while the odd-parity assignment for both the 1.08- and 2.10-MeV levels is from the recent work of Poletti.[8] As a result of the information derived from these previous experiments[1–9] the character of the lower-lying levels of F^{18} has been reasonably well established.

The present experiment was designed to study higher-lying levels with $E_{ex}>3.4$ MeV through proton-gamma coincidence measurements and also angular-correlation measurements in the $O^{16}(He^3,p\gamma)F^{18}$ reaction. Some information on the branching ratios of these levels is available from the results of γ-γ coincidence measurements carried out on this reaction with NaI(Tl) detectors and from singles measurements made with a Ge(Li) detector. The information, resulting from these two experiments, which pertains to the states of $E_{ex}<4$ MeV has been summarized previously.[9] We note with reference to the levels under investigation in the present report that excitation energies of 3724.8 ± 3 keV, 3790 ± 5 keV, and 3838.5 ± 3.5 keV were given[9] for the triplet of levels at $E_{ex}\sim3.8$ MeV, and Doppler-shift attenuation measurements resulted in upper limits on the mean lifetimes of the 3.72- and 3.84-MeV levels of 0.08 and 0.1 psec, respectively. Also forthcoming from these studies[9] but not reported previously are the determination of excitation energies of 4114.9 ± 4 keV and 4230.7 ± 4 keV for the next two excited states. These results were obtained from the spectrum of gamma rays from the $O^{16}(He^3,p\gamma)F^{18}$ reaction measured at $E_{He^3}=6$ MeV, using a 30-cc Ge(Li) detector placed at $\theta_\gamma=90°$ to the beam direction. In the following presentation and discussion of the p-γ correlation measurements, the results of these two experiments have been incorporated in the final establishment of decay schemes and branching ratios.

II. EXPERIMENTAL PROCEDURE

Proton-gamma correlations in the $O^{16}(He^3,p\gamma)F^{18}$ reaction were studied at He^3 bombarding energies of 4.65, 5.40, and 6.40 MeV using the He^{3++} beam from the Brookhaven National Laboratory Van de Graaff accelerator. The target for the He^3 bombardment was an approximately 50 $\mu g/cm^2$ self-supporting foil of SiO. Protons were detected by an annular solid-state detector, which was centered at 180° to the beam direction and 4 cm from the target, subtending an angle θ_p of $(171\pm1.7)°$. A 5×5-in. NaI(Tl) detector was used for the measurement at $E_{He^3}=4.65$ MeV, while a 3×3-in. NaI(Tl) detector was used for the higher bombarding energies. The spectrum of coincidence pulses from the two detectors was analyzed by a TMC 16384-channel two-parameter analyzer operating in a 256 (gamma) ×64 (proton)-channel mode. At each of the three bombarding energies data were acquired for detection angles $\theta_\gamma=0°$, 30°, 45°, 60°, and 90°, with one or more angles repeated as a check on reproducibility. The results of each experimental measurement were transcribed onto magnetic tape for later computer analyses; at the conclusion of the correlation measurements at a given bombarding energy, the individual spectra corresponding to the various θ_γ were added to form a "summed spectrum," which was used to determine decay schemes and branching ratios. Corrections due to correlation effects were later determined, from the results of the correlation analysis, to be small; they were nevertheless applied in the final determination of branching ratios. These procedures were described in more detail previously.[1]

III. RESULTS

Figure 2 illustrates the results of a partial analysis of the data acquired at $E_{He^3}=5.40$ MeV. The upper plot shows the charged particle spectrum measured in coincidence with gamma-ray pulses corresponding to $E_\gamma>0.2$ MeV. In the lower plots we have shown the spectra coincident with 0.94-, 1.04-, and 1.69-MeV gamma-ray photopeaks. The peaks evident in Fig. 2 are labeled according to the F^{18} excitation energies (in MeV). From this we see that the states at 2.52, 3.06, 3.84, and 4.23 MeV deexcite by gamma transitions leading through the 0.94-MeV first excited state of F^{18}, while the levels at 3.13, 3.36, and 3.72 MeV deexcite by transitions leading through the 1.04-MeV second excited state. The 4.11-MeV level is observed to deexcite with roughly equal probability by transitions leading to both the 0.94- and 1.04-MeV levels. The proton peak observed in coincidence with the gamma-ray photopeak at 1.69 MeV corresponds, as will be demonstrated, with the group leading to the 3.79-MeV level.

The energy calibration for these spectra as determined from the identified F^{18} proton groups is shown in the upper figure, where we have indicated also the expected positions of various proton groups from the $C^{12}(He^3,p\gamma)N^{14}$ reaction. It is thus clear that the presence in these data of p-γ coincidences due to the small carbon contamination of the target could not affect our analysis of the F^{18} 3.8-MeV triplet levels. In the region of the F^{18} 4.11- and 4.23-MeV levels we might, however,

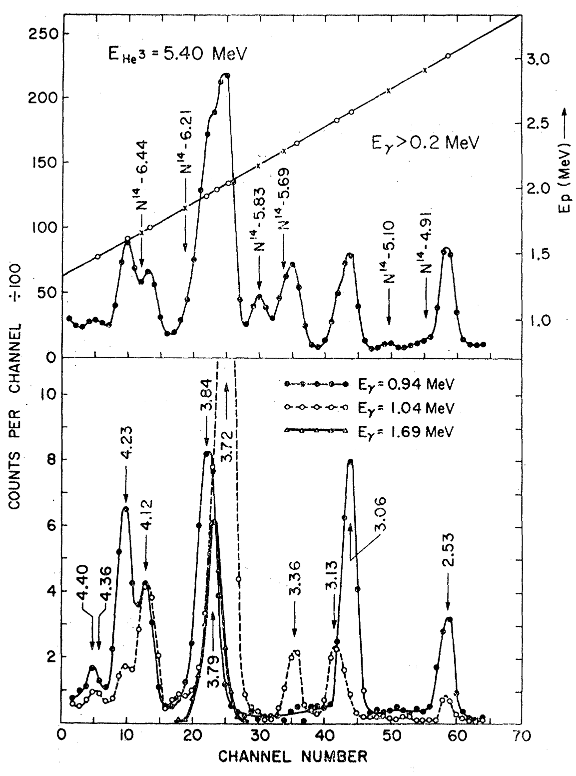

FIG. 2. Partial results of a two-parameter analysis of proton-gamma coincidences from the $O^{16}(He^3,p\gamma)F^{18}$ reaction at a bombarding energy $E_{He^3}=5.40$ MeV. The upper plot shows the charged-particle spectrum measured in coincidence with all gamma-ray pulses of energy $E_\gamma>0.2$ MeV. The lower plot shows the spectra observed in coincidence with 0.94-, 1.04-, and 1.69-MeV gamma-ray photopeaks. The proton groups of the lower plot are identified by the F^{18} excitation energy (in MeV). From the energy calibration shown in the upper plot, as based on this identification, the expected position of various contaminant proton groups from the $C^{12}(He^3,p\gamma)N^{14}$ reaction are indicated. These spectra were measured with an annular solid-state detector at $\theta_p=180°$, and were obtained as the sum of the individual spectra measured at the various angles of the correlation investigation.

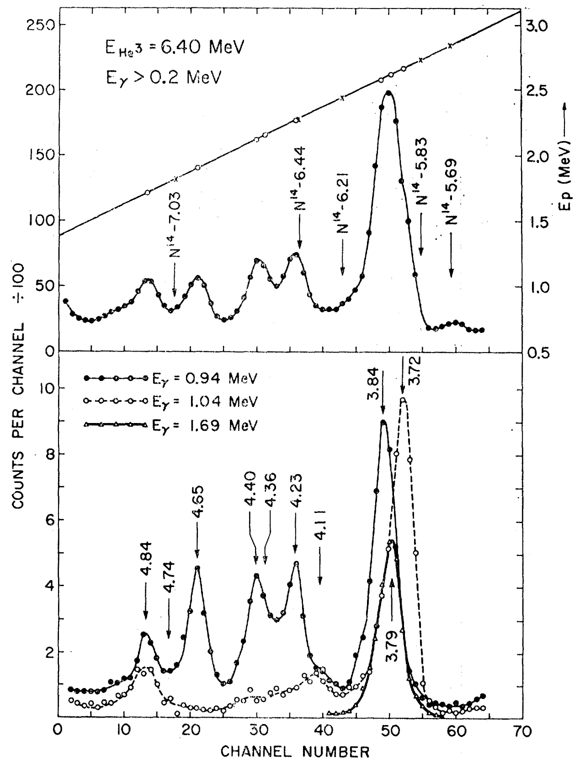

FIG. 3. Partial results of a two-parameter analysis of proton-gamma coincidences from the $O^{16}(He^3,p\gamma)F^{18}$ reaction at a bombarding energy of 6.40 MeV. As in Fig. 2, the plots show the charged-particle spectra measured in coincidence with various regions of gamma-ray energy. The energy calibration (upper figure) is based on the identification in the lower plots of the indicated F^{18} protons groups, which are labeled according to excitation energy (in MeV) of the corresponding F^{18} levels. The expected position of possible contaminant groups from the $C^{12}(He^3,p\gamma)N^{14}$ reaction are indicated.

expect a small contribution due to the N^{14} 6.44-MeV level; this possibility was subsequently accounted for in the determination of branching ratios and correlations for these two F^{18} levels. A similar plot is shown in Fig. 3 for the data acquired at $E_{He^3}=6.40$ MeV. Here we see evidence for population of the 4.36- and 4.40-MeV levels of F^{18} (unresolved) and also for population of the 4.65- and 4.84-MeV levels.

From these results and similar ones obtained for $E_{He^3}=4.65$ MeV, it was a fairly simple matter to obtain the gamma spectra in coincidence with a given proton group, both from the summed spectra and from the individual spectra measured at the various angles θ_γ. From these spectra, branching ratios and experimental correlations were obtained as explained below for the various F^{18} levels studied.

The analysis of the data on the triplet of levels at 3.72, 3.79, and 3.84 MeV was the most difficult, since the resolution of the particle detector was not sufficient to resolve the individual proton groups. However, as is evident from Figs. 2 and 3, the principal modes of deexcitation of the three levels are markedly different and hence were readily deduced from inspection of the net

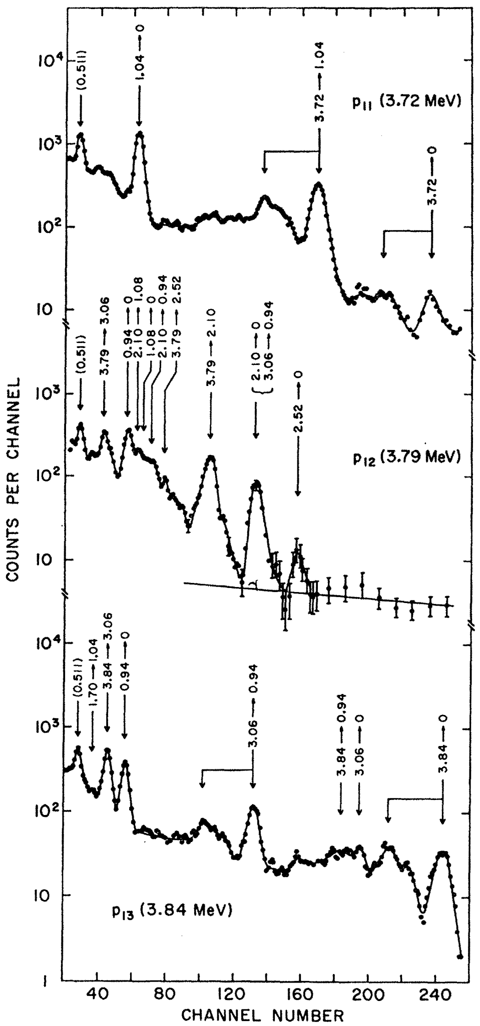

FIG. 4. Spectra of gamma rays from the $O^{16}(He^3,p\gamma)F^{18}$ reaction measured in coincidence with proton groups p_{11}, p_{12}, and p_{13} populating, respectively, the 3.72-, 3.79-, and 3.84-MeV levels of F^{18}. For each spectrum the gamma-ray peaks are labeled by the energies (in MeV) of the initial and final states between which the transitions occur. These assignments are discussed in the text. These spectra were obtained from the two-parameter data for $E_{He^3}=5.40$ MeV by unfolding the separate contributions due to the unresolved triplet of levels as shown in Fig. 2.

2-parameter data. The major decay mode of the 3.72-MeV level is via the $3.72\rightarrow1.04\rightarrow0$ cascade giving rise to gamma rays of energy 2.69- and 1.04-MeV. Evidence is also seen for a weak $3.72\rightarrow0$ transition. The 3.84-MeV level deexcites primarily by transitions to the ground state and to the 3.06-MeV level, giving rise to gamma rays of energy 3.84, 3.06, 2.12, 0.94, and 0.78 MeV. By a process of elimination, it was subsequently ascertained that the principal deexcitation of the 3.79-MeV level is via the cascade transition $3.79\rightarrow2.10$, since we see a 1.69-MeV gamma ray and also those gamma rays which characterize the deexcitation of the 2.10-MeV level.

Having deduced the principal decay modes of these three unresolved levels, the gamma spectra due to deexcitation of each state was extracted from the data. For example, from the data for $E_{He^3}=5.40$ MeV (Fig. 2) the spectrum due purely to deexcitation of the 3.72-MeV level was obtained as the sum of channels (25+26+27) minus the sum of channels (20+17+18). The resultant spectrum is shown in Fig. 4, as are also the spectra thus determined to be in coincidence with proton groups p_{12} and p_{13}.

The 3.72-MeV Level of F^{18}

From the data of Fig. 4 ($E_{He^3}=5.40$ MeV) and from similar data for the other two bombarding energies, we compute branching ratios of $(6\pm3)\%$ and $(94\pm3)\%$ for transitions from the 3.72-MeV level to the ground state and to the 1.04-MeV second excited state, respectively. (We note that the observed 3.72-MeV ground-state transition is energetically distinguishable from the $3.84\rightarrow0$ transition which appears so strongly in the net unresolved spectrum.) No evidence is obtained for other possible modes of deexcitation. The results for the branching of the F^{18} 3.72-MeV level are summarized in Table I, where we have quoted an average of the present results with those of Refs. 7 and 9.

The experimental angular correlation of the $3.72\rightarrow1.04$ transition extracted from the data for $E_{He^3}=4.65$ MeV is shown in Fig. 5. The results of an even-order Legendre polynomial fit to the data, of the form

$$W(\theta)=I_\gamma \sum_\nu a_\nu P_\nu(\cos\theta),$$

are given in Table II. The table lists the solutions for a_ν ($a_0\equiv1$) obtained for $\nu_{max}=2$ and also for $\nu_{max}=4$, together with the values of χ^2 (normalized) obtained for

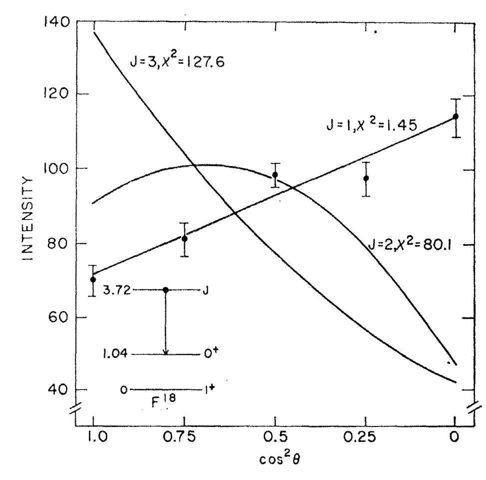

FIG. 5. Proton-gamma angular-correlation results for the F^{18} 3.72-MeV level. The solid circles and error bars show the experimental data obtained from measurements of the $O^{16}(He^3,p\gamma)F^{18}$ reaction at $E_{He^3}=4.65$ MeV. The curves show the best fits to the data obtained, as indicated in the insert, for assumed spins of $J=1$, 2, and 3 for the 3.72-MeV level. For each assumption, the minimum value of χ^2, the goodness-of-fit parameter, is indicated. From this we see that possibilities $J=2$ and $J=3$ are excluded to better than 99.9% confidence. In conclusion, a unique $J=1$ assignment is obtained for the 3.72-MeV level.

TABLE I. Summary of branching ratios (or limits) determined for gamma-ray transitions in F^{18} from the listed initial states E_i to various final states E_f. As explained in the text, this summary is based on the present work and on that given in Refs. 7 and 9. Values are in percent.

E_f (MeV) \ E_i (MeV)	3.72	3.79	3.84	4.11	4.23	4.36	4.40	4.65	4.84
0	8±2	<15	39±4	5±3	31±5			<5	<6
0.94	<6	<10	5±4	<8	52±5	<20	(⩽30)	15±5	<4
1.04	92±2	<15	<4	<8	<5			<5	64±4
1.08	<15	<15	<3	<8	(⩽5)[a]			<5	<15
1.13	<10	<10	<3	<8	<10		(100)[b]	85±5	<15
1.70	<6	<10	4±4	<8	5±3			<5	<10
2.10	<10	76±10	<5	<15	12±3			<10	<15
2.52	<3	4±4	<2	<15	<4			<10	<10
3.06	<5	20±8	52±4	95±3	<3	(100)[b]		<4	36±4
3.13	<3	<10	<6	<13	(⩽5)[a]			<4	<15
3.36	<4	<20	<9	<10	<5			<3	<15

[a] One or both of these transitions may occur. Both possibilities would give rise to 1.08-MeV gamma rays and hence we may not distinguish between them.
[b] Assumed.

each fit. The theoretical correlation curves computed for various assumed values J for the spin of the 3.72-MeV level are also shown in Fig. 5. The computed curves for $J=2$ and for $J=3$ clearly fail to match the datum points as is evidenced also by the minimum values of χ^2. The fit for $J=1$ is, however, quite satisfactory. Therefore we have determined that the 3.72-MeV level has $J=1$ to a confidence of better than 99.9%. We note that since both the 1.04- and 1.08-MeV levels have $J=0$, the correlation analysis would not be altered by the presence of a possible (<15%) 3.72 → 1.08 branch.

In summary then, the 3.72-MeV level has $J=1$, and de-excites primarily by dipole emission to the 1.04-MeV state with a weak transition to the ground state. The branches are found to be (92±2)% and (8±2)%, respectively.[7,9] From the limit imposed previously[9] for the mean lifetime of the 3.72-MeV level, $\tau<0.08$ psec, we compute a lower limit to the level width: $\Gamma_\gamma(3.72) > 8.2\times10^{-3}$ eV. Allowing for 2 standard deviations in the branching ratios as quoted in Table II, we compute the strength of the 3.72 → 1.04 transition, in Weisskopf units[10] (W.u.), to be either $|M(E1)|^2 > 0.0008$ W.u. or $|M(M1)|^2 > 0.02$ W.u. depending on whether the transition is $E1$ or $M1$, respectively. Both values are reasonable, and hence the parity of the 3.72-MeV level cannot be determined from this information.

The 3.84-MeV Level of F^{18}

In addition to those gamma rays resulting from transitions to the ground state and to the 3.06-MeV state, evidence is seen (Fig. 4) for a gamma ray of energy 2.9 MeV, which appears to be definitely in coincidence with the 3.84-MeV proton group, and which we ascribe to the transition 3.84 → 0.94. A weak gamma ray of energy 0.66 MeV, characterizing the deexcitation of the 1.70-MeV level, also appears. From these data we compute the following branching ratios (in percent): 3.84 → 0 (41±4), 3.84 → 0.94 (5±3), 384 → 1.70 (4±3), and 3.84 → 3.06 (50±4). The relative intensities

TABLE II. Partial results of proton-gamma angular correlations measured in the $O^{16}(He^3,p\gamma)F^{18}$ reaction. The transitions in F^{18} are indicated in column 2, as resulting from deexcitation of the initial levels indicated in column 1. Columns 3–7 give the coefficients a_ν for an even-order Legendre polynomial fit to the correlation data of the form $W(\theta)=I_\gamma \sum_\nu a_\nu P_\nu(\cos\theta)$ (with $a_0\equiv1$) for $\nu_{max}=2$ and $\nu_{max}=4$. The corresponding values of χ^2 (the goodness-of-fit parameter) are indicated for both cases. The He^3 bombarding energies used in each measurement are given in column 8. In some cases we have presented a weighted average of the measurements at two different energies, as indicated by the brackets and explained further in the text.

E_{ex} (MeV)	Transition	$\nu_{max}=2$ a_2	χ^2	$\nu_{max}=4$ a_2	a_4	χ^2	E_{He^3} (MeV)
3.72	3.72 → 1.04	−0.28±0.04	1.4	−0.26±0.04	−0.04±0.04	1.8	4.65
3.79	3.79 → 2.10	−0.18±0.06	0.6	−0.20±0.06	+0.06±0.06	0.5	4.65
3.84	3.84 → 0	+0.38±0.05	10.0	+0.45±0.04	−0.28±0.04	0.6	{4.65 + 6.40}
	3.84 → 3.06	+0.26±0.04	2.0	+0.26±0.04	−0.01±0.05	2.9	
4.11	4.11 → 3.06	−0.47±0.06	0.3	−0.45±0.08	−0.04±0.06	0.3	5.40
4.23	4.23 → 0	−0.32±0.07	0.3	−0.34±0.08	−0.05±0.07	0.3	{5.40 + 6.40}
4.36	4.36 → 3.06	−0.19±0.12	1.0	−0.23±0.13	+0.10±0.14	1.2	6.40
4.65	4.65 → 1.13	−0.58±0.14	0.3	−0.58±0.14	−0.05±0.14	0.2	6.40
4.84	4.84 → 1.04	+0.4 ±0.09	0.5	+0.43±0.10	−0.06±0.10	0.6	6.40

[10] D. H. Wilkinson, in *Nuclear Spectroscopy*, edited by F. Ajzenberg-Selove (Academic Press Inc., New York, 1960), Part B, p. 862 ff.

TABLE III. Results of a χ^2 analysis of proton-gamma angular correlations in the $O^{16}(He^3,p\gamma)F^{18}$ reaction. The initial F^{18} levels and the transitions studied are identified in columns 1 and 2. Assumed spin sequences are given in column 3; with the exception of the 1.13-MeV level, the final-state spins are known in all cases. The solutions for x, the $(L+1)/L$ mixing ratios for the indicated transitions, are given for these assumed initial-state spins. Remaining possibilities for spins of the initial state have been eliminated with better than 99% confidence.

E_{ex} (MeV)	Transitions fitted	Assumed spin sequence	Solutions for x	χ^2
3.72	$3.72 \rightarrow 1.04$	$1 \rightarrow 0$	$x \equiv 0$	1.4
3.79	$3.79 \rightarrow 2.10$	$1 \rightarrow 2$	(x=undefined)	0.6
		$2 \rightarrow 2$	$x > 0.36$ or $\|x\| = \infty$	0.6
		$3 \rightarrow 2$	$x = -(0.08_{-0.05}^{+0.08})$ or $x = +(4.7_{-1.0}^{+3.1})$	0.5
3.84	$3.84 \rightarrow 0$	$2 \rightarrow 1$	$-20 < x < -0.58$	0.6
		$3 \rightarrow 1$	$x = +(0.07_{-0.07}^{+0.05})$ or $x = +(3.7_{-0.7}^{+1.0})$	0.6
	$3.84 \rightarrow 3.06$	$2 \rightarrow 2$	$x = +(0.05_{-0.43}^{+0.14})$ or $x = -(2.7 \pm 0.8)$	1.3
		$3 \rightarrow 2$	$x = -(0.33_{-0.06}^{+0.05})$; $\|x\| > 0.21$	1.3
4.11	$4.11 \rightarrow 3.06$	$1 \rightarrow 2$	$x < -0.11$	0.5
		$2 \rightarrow 2$	$x = +(1.5_{-0.8}^{+2.5})$; $x > 0.5$	0.5
		$3 \rightarrow 2$	$x = +(0.09_{-0.09}^{+0.12})$ or $x = +(2.2 \pm 0.4)$	0.5
4.23	$4.23 \rightarrow 0$	$1 \rightarrow 1$	(x=undefined)	0.4
		$2 \rightarrow 1$	$x = +(0.0_{-0.12}^{+0.18})$ or $x = +(2.7 \pm 1.0)$	0.4
4.36	$4.36 \rightarrow 3.06$	$0 \rightarrow 2$	$x \equiv 0$	1.0
		$1 \rightarrow 2$	(x=undefined)	1.0
		$2 \rightarrow 2$	$x > 0.1$	0.8
		$3 \rightarrow 2$	$x = -(0.07 \pm 0.07)$ or $x = +(4.5_{-1.2}^{+3.6})$	0.9
4.65	$4.65 \rightarrow 1.13$	$3 \rightarrow 5$	$x < -0.27$ or $x > +4.7$	0.2
		$4 \rightarrow 5$	$x = -(3.3_{-1.5}^{+3.0})$ or $x = -(0.31_{-0.16}^{+0.40})$	0.2
		$5 \rightarrow 5$	($x > 0.7$)	1.5
		$6 \rightarrow 5$	$x = +(0.18 \pm 0.15)$ or $x > 0.7$	0.2
4.84	$4.84 \rightarrow 1.04$	$1 \rightarrow 0$	$x \equiv 0$ (dipole)	0.5
		$2 \rightarrow 0$	$x \equiv 0$ (quadrupole)	0.5

of the principal deexcitation gamma rays are in agreement with those reported by Gorodetzky *et al.*[7] and we thus give an average of these values in Table I. The limits on other possible branches quoted in Table I are derived from the present work and Ref. 9. From the lifetime measurement for the 3.84-MeV level,[9] which has restricted the mean life to be $\tau < 0.1$ psec, and using the branching ratios summarized in Table I, we compute a total radiative width for the 3.84-MeV level of $\Gamma_\gamma > 6.6 \times 10^{-3}$ eV and partial widths as follows: $\Gamma_\gamma(3.84 \rightarrow 0) > 2.2 \times 10^{-3}$ eV and $\Gamma_\gamma(3.84 \rightarrow 3.06) > 2.8 \times 10^{-3}$ eV.

The experimental results obtained at the three bombarding energies for the $3.84 \rightarrow 0$ angular correlation were found to be markedly similar, as were also the results of our analysis of these data. Hence we have chosen to present, as illustrated in Fig. 6, an analysis of the "net" correlation data obtained as a properly weighted sum of the data from the three separate measurements. The experimental data are shown in the upper portion of Fig. 6. Results of a Legendre polynomial fit to these data (and also to the $3.84 \rightarrow 3.06$ correlation data) are summarized in Table II. From the large coefficient of $P_4(\cos\theta)$ we can immediately conclude that the spin of the 3.84-MeV level has $J \geq 2$. This is in agreement with a previous observation[11] which can now be interpreted as confirming the $J \geq 2$ restriction for the 3.84-MeV level. The results of a χ^2 analysis of the present data are presented in the lower portion of Fig. 6. In these curves χ^2, representing the goodness of fit to the experimental data, is plotted as a function of x, the multipole amplitude ratio describing $(L+1)/L$ mixing in the $3.84 \rightarrow 0$ transition. Throughout this work we shall use the phase convention of Poletti and Warburton[3] for $EL/M(L+1)$ mixtures. These curves were generated by a computer program, described previously,[1,3] which adjusts the population parameters $P(0)$ and $P(1)$ to obtain a best fit to the experimental data for discreet values of x in the range $-\infty \leq x \leq +\infty$. Plots are shown for various assumed values of J, the spin of the 3.84-MeV level. The solid curves are computed for an ideal proton detector at $\theta_p = 180°$; the dashed curve gives our estimate of the maximum possible effect of the small deviation of θ_p from 180° (FSE).[3] From these curves we see that possible assignments $J=0$ and $J=1$ are rejected with better than 99.9% confidence. However, both $J=2$ and $J=3$ are found to be acceptable solutions for particular values of x, as indicated. These solutions for x are summarized in Table III. The solid curves of the upper portion of Fig. 6 show the computed correlations corresponding to the minima in χ^2 for $J=0$, 1, 2, 3; i.e., the best fits obtained under different assumptions for J.

We next examine the $3.84 \rightarrow 3.06$ correlation data (Table II). The results of a χ^2 analysis of these data to determine possible quadrupole-dipole mixing in the $3.84 \rightarrow 3.06$ transition are summarized in Table III. Solutions are obtained for both possible spin assignments $J=2$ and $J=3$ for the 3.84-MeV level. We now consider in sequence these two possible spin assignments for the 3.84-MeV level, taking into consideration also the limits quoted above on the transition widths.

If $J=3$, then the $3.84 \rightarrow 3.06$ transition has a signifi-

[11] E. K. Warburton, J. W. Olness, and D. E. Alburger, Phys. Rev. **140**, B1202 (1965).

cant quadrupole admixture, $|x|>0.21$ to 99.9% confidence. The strength of this component is either $|M(E2)|^2>6\times10^2$ W.u. or $|M(M2)|^2>3.8\times10^3$ W.u. depending upon whether the quadrupole component is $E2$ or $M2$, respectively. Both possibilities exceed the most generous sum-rule limit[10] $|M|^2\leq Z^2$ and hence the spin of the 3.84-MeV level may not be 3.

For a $J=2$ assignment to the 3.84-MeV level we conclude that the $3.84\rightarrow3.06$ transition must be approximately pure dipole, since the larger solution for x (Table III) corresponds to quadrupole strengths exceeding this sum-rule limit.[10] From the correlation results summarized in Table III we have the restriction on quadrupole/dipole mixing in the $3.84\rightarrow0$ ground-state transition of $-20<x<-0.58$, where the limit is to 99.9% confidence. If $J^\pi=2^-$, then the quadrupole component in this ground-state transition would be $M2$ of strength $|M(M2)|^2>8$ W.u. This is highly unlikely, since it corresponds to a strength more than 10 times greater than the strongest authenticated isotopic-spin inhibited $M2$ transition observed previously.[12,13]

We may summarize then by saying that the 3.84-MeV level has $J=2$ and is almost certainly of even parity. For a $J^\pi=2^+$ assignment, the restriction on the $E2$ strength of the ground-state transition (in W.u.) is $0.3<|M(E2)|^2<1.1$. The $3.84\rightarrow3.06$ transition is then essentially pure magnetic dipole of strength $|M(M1)|^2>0.28$ W.u. A $\Delta T=0$ dipole transition of this strength would be quite surprising.[12,13] Thus the $3.84\rightarrow3.06$ transition is almost certainly $\Delta T=1$ which gives further support to a $T=1$ assignment for the 3.06-MeV level.

The 3.79-MeV Level of F^{18}

The strongest gamma ray originating from the 3.79-MeV level is that of energy 1.69 MeV resulting from the $2.79\rightarrow2.10$ transition (Fig. 4). We also see a 2.1-MeV gamma ray and the complex of gamma rays at 1 MeV resulting from the known deexcitation of the 2.10-MeV level. The intensity of the 2.1-MeV gamma ray is however too strong to arise solely from the $2.10\rightarrow0$ transition, and instead arises in part from the deexcitation of the 3.06-MeV level, which is populated via a $3.79\rightarrow3.06$ transition giving rise to the 0.73-MeV gamma ray which appears prominently in the deexcitation spectrum. Evidence also appears for a gamma ray of energy ~1.27 MeV, which could arise from a $3.79\rightarrow2.52$ transition. The measured gamma-ray intensities fit well with the assumption that the 3.79-MeV level decays via transitions to the 2.10-, 2.52-, and 3.06-MeV levels, and we finally compute the branching ratios and upper limits given in Table I. Partial results of the angular-correlation analysis of the $3.79\rightarrow2.10$ transition are summarized in Table II. The results of χ^2 analyses of these data restricts the spin of the 3.79-MeV level to $J=1$, 2, or 3, with the restrictions on the quadrupole/dipole mixing ratios in the $3.79\rightarrow2.10$ transition which are given in Table III. Spins $J=0$ or $J>3$ are eliminated with better than 99.9% confidence.

No attempt was made to fit the $3.79\rightarrow3.06$ correlation, since the 0.73-MeV gamma ray was not resolved from the 0.78-MeV gamma ray resulting from the $3.84\rightarrow3.06$ transition. In this respect we note that the relative intensities of these two gamma rays in the "net" spectrum of gamma rays from the unresolved triplet were $I_\gamma(0.78)/I_\gamma(0.73)\sim5/1$. Since in the analysis of the $3.84\rightarrow3.06$ correlation data, the effect of possible $3.79\rightarrow3.06$ contributions were eliminated to better than 80%, the net uncertainty in the measured $3.84\rightarrow3.06$ correlation due to this problem was at most 4%. This uncertainty was incorporated in our analysis of the $3.84\rightarrow3.06$ angular correlation.

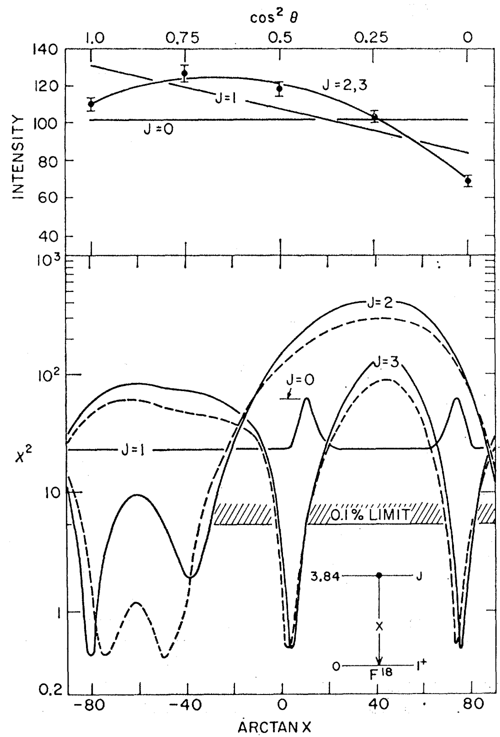

FIG. 6. Proton-gamma angular correlations for the F^{18} $3.84\rightarrow0$ transition resulting from population of the 3.84-MeV level in the $O^{16}(He^3,p\gamma)F^{18}$ reaction. The points with error bars (upper plot) show the experimental correlation data. The results of a χ^2 analysis of these data are shown in the lower figure. Here we have plotted χ^2, representing the goodness of fit to the experimental data, as a function of arctan$x$, where x is the $(L+1)/L$ mixing ratio in the $3.84\rightarrow0$ transition. These curves were calculated for an ideal detector of negligible solid angle placed at $\theta_p=180°$; the dashed curves show our estimates of the maximum possible finite-size-effect (FSE). Plots are shown for assumed values $J=1$, 2, 3 for the F^{18} 3.84-MeV level; the minimum value of χ^2 for a $J=0$ assumption is also indicated. The probability that χ^2 exceeds the limit marked as 0.1% is just 0.1%. From this we see that possibilities $J=0$ and $J=1$ are excluded to better than 99.9% confidence. For the possibilities $J=2$ and $J=3$, the mixing ratios x are restricted to values corresponding approximately to the minima in the χ^2 plots. The best-fitting correlations for $J\leq3$ are shown in the upper plot for comparison with the experimental data.

[12] E. K. Warburton, in *Isobaric Spin in Nuclear Physics*, edited by J. D. Fox and D. Robson (Academic Press Inc., New York, 1966), pp. 90–112.
[13] E. K. Warburton, Phys. Rev. **113**, 595 (1959).

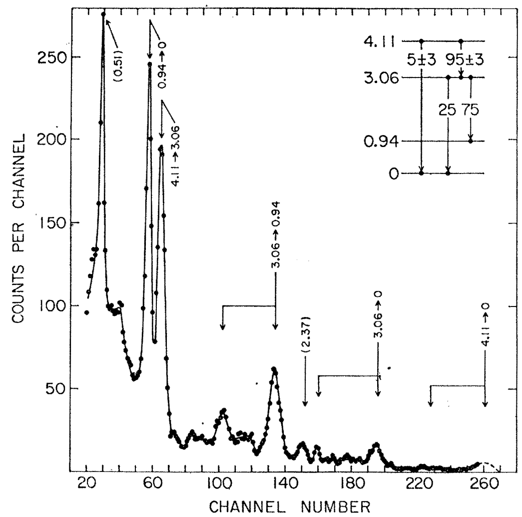

FIG. 7. Spectrum of gamma rays from the $O^{16}(He^3,p\gamma)F^{18}$ reaction measured in coincidence with proton group p_{14} corresponding to population of the F^{18} 4.115-MeV level. Transitions are labeled according to the excitation energies (in MeV) of the initial and final levels between which the transitions occur. These data were obtained from the two-parameter spectrum of proton-gamma coincidences measured at $E_{He^3}=5.40$ MeV, and represent the sum of the data measured at the various correlation angles. The decay scheme deduced from these data is shown in the insert.

The 4.11-MeV Level of F^{18}

That the principal deexcitation of the 4.11-MeV level occurs via the $4.11\rightarrow3.06$ cascade is readily deduced from the spectrum shown in Fig. 7. The data extend only to channel 256; we have indicated the maximum possible $4.11\rightarrow0$ component consistent with these data. A more critical determination of the ground-state intensity was made by examining the proton spectra in coincidence with gamma channels (210–256) which gives evidence for an $\sim5\%$ ground-state transition. These results are presented in Table III, where we have included possible summing effects in computing thc intensity of the ground-state transition.

The results of χ^2 analyses of the $4.11\rightarrow3.06$ correlation data (see Table II) are summarized in Table III. Spins of $J=1$, 2, or 3 are allowed by these data, with the multipole mixing restrictions given. Again the possibilities $J=0$ and $J>3$ are excluded to 99.9% confidence. The angular distributions of the 3.06-, 2.13-, and 0.94-MeV transitions were also extracted, and a simultaneous 4-distribution fit was made to the data on the $4.11\rightarrow3.06$, $3.06\rightarrow0$, and $3.06\rightarrow0.94\rightarrow0$ transitions. The spins and gamma-ray multipolarities involved in the latter three transitions are known from previous measurements.[1] These results were in agreement with, but unfortunately no more restrictive than, the results obtained from the analysis of the $4.11\rightarrow3.06$ transition alone.

In conclusion, the 4.11-MeV level has $J=1$, 2, or 3; the quadrupole/dipole mixing ratios for each of these possibilities are summarized in Table II. These results are in good agreement with the conclusions reported by Gorodetzky *et al.*[7]

The 4.23-MeV Level of F^{18}

As is evident from Fig. 8 the gamma-ray spectrum of the 4.23-MeV level is complex. The principal decay occurs via the $4.23\rightarrow0$ and $4.23\rightarrow0.94$ transitions. Evidence is also seen for gamma rays resulting from the transition $4.23\rightarrow2.10$ and less clearly from a $4.23\rightarrow1.70$ transition. These gamma-ray intensities fit well with the indicated assignments resulting in the branching ratios and limits summarized in Table I. The exception is for the 1.08-MeV peak, which appears too strong to be explained by the suggested deexcitations. From its energy it can arise either from a $4.23\rightarrow3.13$ transition or a $4.23\rightarrow1.08\rightarrow0$ cascade and is so indicated by the appropriate entry ($\leqslant5$) in Table III. From the correlations measured for the $4.23\rightarrow0$ transition (see Table II) we arrive at the spin limitations and multipole mixing conclusions summarized in Table III. The correlation data on the $4.23\rightarrow0.94\rightarrow0$ cascade were also fitted; again, it was found that these data limit the spin of the 4.23-MeV level to $J=1$ or 2, but no restrictions are imposed on possible mixings in the $4.23\rightarrow0.94$ transition.

The 4.36- and 4.40-MeV Levels of F^{18}

The gamma-ray deexcitation spectrum of these unresolved doublet levels measured at a bombarding energy of 6.40 MeV (corresponding to the particle spectrum of Fig. 3) is shown in Fig. 9. From examination of the proton spectra coincident with various gamma-ray photopeaks, it is determined that the 1.30-MeV

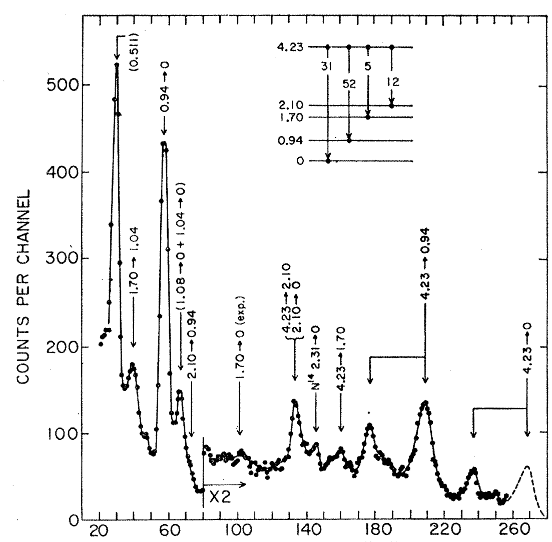

FIG. 8. Spectrum of gamma rays from the $O^{16}(He^3,p\gamma)F^{18}$ reaction measured in coincidence with proton group p_{15} (4.23-MeV level). The various F^{18} transitions are identified according to the excitation energies of the initial and final states; the decay scheme deduced from these data is shown in the insert.

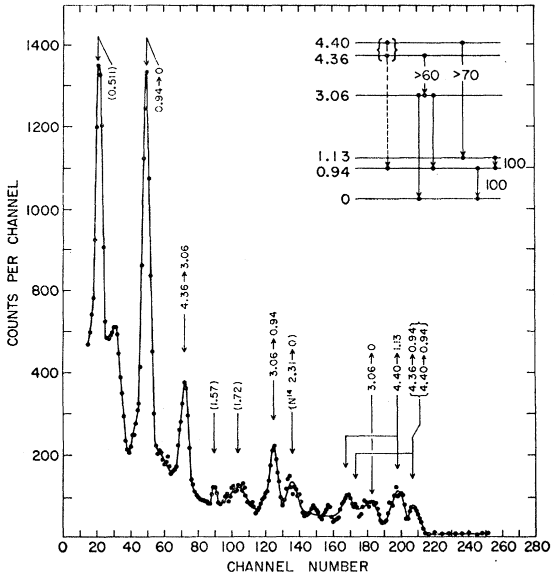

FIG. 9. Spectrum of gamma rays from the $O^{16}(He^3,p\gamma)F^{18}$ reaction measured at $E_{He^3}=6.40$ MeV in coincidence with the unresolved proton groups p_{16} and p_{17} populating, respectively, the 4.36- and 4.40-MeV levels of F^{18}. From these data it is determined that the primary deexcitation of these two levels occurs via $4.40 \rightarrow 1.13$ and $4.36 \rightarrow 3.06$ cascades, as indicated in the insert. The peak at $E_\gamma=3.43\pm0.02$ appears to result primarily from a $4.36 \rightarrow 0.94$ transition, but its assignment is uncertain.

gamma ray is associated with the 4.36-MeV level, resulting from the $4.36 \rightarrow 3.06$ transition, while the *stronger* high-energy line arises from the $4.40 \rightarrow 1.13$ transition. Thus the major decay modes of these two levels are quite clear, and explain the presence of the prominent peaks of Fig. 9, with the exception noted as follows: the somewhat less-intense high-energy gamma ray, of energy (3.43 ± 0.02) MeV, cannot be assigned on the basis of its energy to either of the two indicated transitions, and may in fact arise in part from each. However, an upper limit of 20% can be assigned to a possible $4.36 \rightarrow 0.94$ transition, which permits us to indicate the limits outlined in Table I. The $4.36 \rightarrow 3.06$ correlation was observed to be approximately isotropic, as indicated in Table II. These results are consistent with possible spin assignments $J=0, 1, 2, 3$ as indicated in Table III. Possibilities $J>3$ are eliminated to 99% confidence.

The 4.65-MeV Level of F^{18}

From the presence of strong 3.52- and 0.94-MeV gamma rays in the de-excitation spectrum of the 4.65-MeV level (Fig. 10) we deduce that the principal de-excitation occurs via the cascade $4.65 \rightarrow 1.13 \rightarrow 0.94 \rightarrow 0$. Evidence is also seen for a weak $4.65 \rightarrow 0.94$ transition. In extracting the angular correlation of the $4.65 \rightarrow 1.13$ transition, account was taken of the effect of this weaker $4.65 \rightarrow 0.94$ transition. The results of a χ^2 analysis of these correlation data (Table II) assuming the most probable spin $J_B=5$ for the 1.13-MeV level, are summarized in Table III for various assumed spins J_A for the 4.65-MeV level.

The mean lifetime of the 4.65-MeV level is not known, but a crude limit $\tau<10^{-7}$ sec is set from the coincidence circuit resolving time. This is sufficient to rule out the possibilities $J_A=0$ or $J_A=1$ since for these cases the $4.65 \rightarrow 1.13$ transition would necessarily be of multipolarity $L\geqslant4$. From a fit to the correlation data assuming $J_A=2$, we find that the mixing ratio x for $(L=4)/(L=3)$ radiations is $|x|>0.4$; thus this possibility is similarly ruled out.

The remaining possibilities for J_A are summarized in Table III. We note that for $J_A=4$ or $J_A=6$ the correlation data are consistent with the $4.65 \rightarrow 1.13$ transition being pure dipole. However, for the possibility $J_A=5$, the radiation must have a significant quadrupole admixture.

These data on the $4.65 \rightarrow 1.13$ correlation were also examined to see what restrictions could be placed on the spin of the 1.13-MeV level. Under the assumption that the 4.65-MeV level is indeed $J_A=4$, we find that the spin of the 1.13-MeV level is restricted to values $J_B=3$, 4, 5; other possibilities are excluded to better than 99.9% confidence. For the possibilities $J_B=3$ or $J_B=5$, the mixing of quadrupole/dipole radiation is consistent with values $x=0$, while for $J_B=4$ the quadrupole/dipole mixing is restricted to values $x>0.6$.

The 4.84-MeV Level of F^{18}

The 4.84-MeV level is observed to deexcite by transitions to the 1.04- and 3.06-MeV levels with

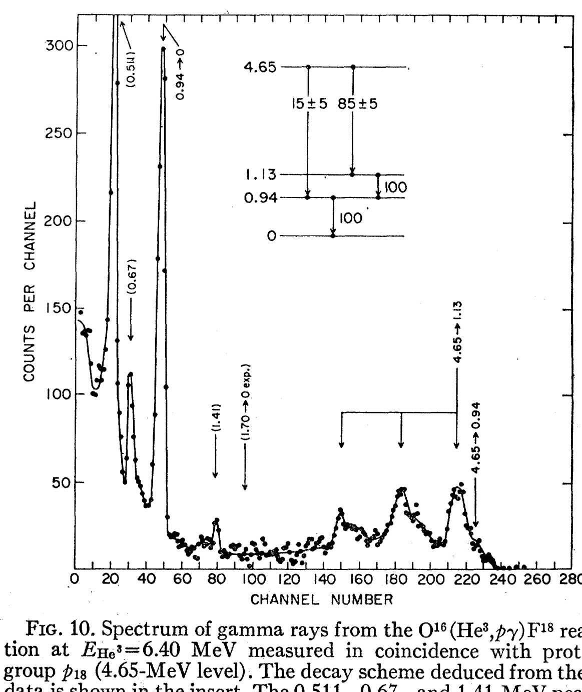

FIG. 10. Spectrum of gamma rays from the $O^{16}(He^3,p\gamma)F^{18}$ reaction at $E_{He^3}=6.40$ MeV measured in coincidence with proton group p_{18} (4.65-MeV level). The decay scheme deduced from these data is shown in the insert. The 0.511-, 0.67-, and 1.41-MeV peaks apparently result from an incomplete removal of background contributions to the spectrum.

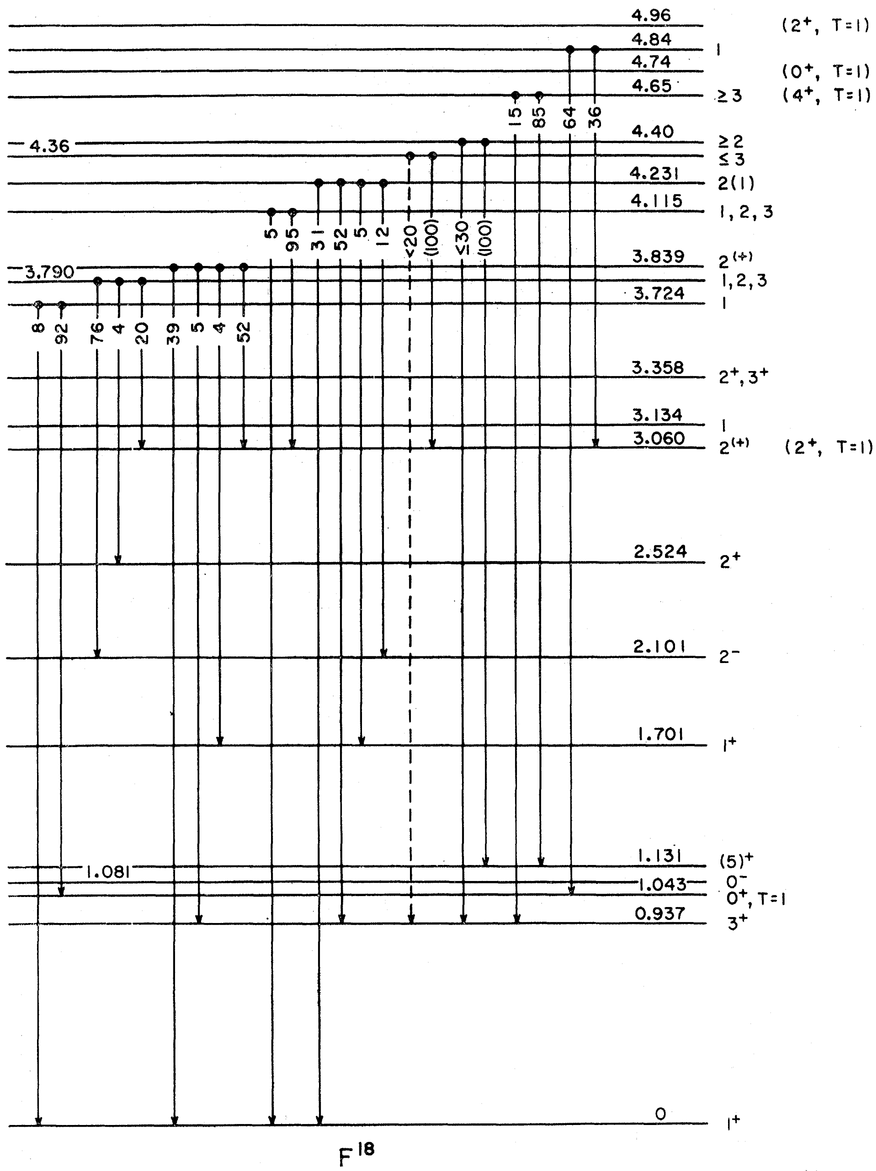

FIG. 11. Summary of presently available information on the spin-parity assignments and branching ratios for those F^{18} levels of $3.4<E_{ex}<5$ MeV, as based on a synthesis of the present work with that of Refs. 1, 7, and 9 of the text. Uncertain or less probable assignments are given in parentheses. In the far right-hand column we have labeled the most likely candidates for the $T=1$ analogs of the lowest four excited states of O^{18}.

branching ratios of $(60\pm10)\%$ and $(40\pm10)\%$, respectively. These results are in agreement with the corresponding values $(65\pm4)\%$ and $(35\pm4)\%$ reported by Gorodetzky *et al.*[7]; we list the average values in Table I. A χ^2 analysis of the correlation data on the $4.84\rightarrow1.04$ transition eliminates, with a certainty of 99.9%, all possibilities for the spin of the 4.84-MeV level save $J=1$ and $J=2$, as indicated in Table III.

IV. DISCUSSION OF RESULTS

Of the 10 levels of F^{18} previously reported in the range of excitation energies $3.4<E_{ex}<4.9$ MeV, we have observed all but one (the 4.74-MeV level) in the present study of p-γ coincidences in the $O^{16}(He^3,p\gamma)F^{18}$ reaction. Angular-correlation studies have resulted in definite spin assignments of $J=1$ for the F^{18} 3.72-MeV level and of $J=2$ for the F^{18} 3.84-MeV level. The latter conclusion is based in part on the previously reported[9] limit on the mean lifetime of the 3.84-MeV level, which also gives a very strong preference for an even-parity assignment for this level.

For the remaining levels studied (six) restrictions were imposed on possible spin assignments and on possible $(L+1)/L$ mixing in the various deexcitation transitions, as summarized in Table III.

The level diagram of Fig. 11 is presented as a schematic summary of the information available on these higher-lying levels of F^{18}. As indicated in Sec. III, the decay schemes and branching ratios deduced from the present experiment are in satisfactory agreement with those of Gorodetzky *et al.*,[7] and hence we have chosen to present in Fig. 11 (and in Table I) a synthesis of these results, which incorporates also the results of Ref. 4. It is similarly found that there is satisfactory agreement between the spin-parity assignments, or restrictions, given in the present report and those expressed independently by Gorodetzky *et al.*[7] These authors also deduce a $J=1$ assignment for the 3.72-MeV level. The restrictions imposed by them on the spin-parity of the 3.84-MeV level are consistent with the present determination of $J^\pi=2^{(+)}$. They obtain a unique assignment of $J=1$ for the 4.84-MeV level, and obtain a strong preference for a $J=2$ assignment for the 4.23-MeV level.

For the remaining levels, although the conclusions on allowed spins and multipole mixing ratios as based on the two separate experiments are found to be consistent, they are unfortunately not more restrictive jointly than each was independently.

A considerable amount of information has been gained on the triplet of levels at approximately 3.8 MeV. The 3.72-MeV level is of $J=1$; its parity may be either even or odd however, since the dipole strengths are found to be reasonable in either case. The 3.84-MeV level is of $J=2$; its parity is almost certainly even, in which case the strength of the $3.84\rightarrow3.06$ transition is consistent with that expected for a magnetic dipole transition of $\Delta T=1$. Similarly, the observed weak transitions to the 0.94-MeV state ($J^\pi=3^+$) and to the 1.70-MeV state ($J^\pi=1^+$) seem reasonable since they would be $E2/M1$ transitions of $\Delta T=0$. It has been pointed out previously[9] that the 3.79-MeV level is a likely candidate for the $J^\pi=3^-$ member of the group of odd-parity levels which include those at 1.08 MeV ($J^\pi=0^-$), 2.10 MeV ($J^\pi=2^-$), and possibly 3.13 MeV (suspected $J^\pi=1^-$). The previously noted decay of the 3.79-MeV level to the 2.10-MeV level ($J^\pi=2^-$) and also to the 3.06-MeV level ($J^\pi=2^+$) are consistent with this expectation. The weak transition to the $J^\pi=2^+$ 2.52-MeV level is also reasonable.

With respect to those states of $E_{ex}>4$ MeV it is clear that a considerable amount of additional information is yet needed to clarify the experimental picture. We note that additional lifetime measurements would be useful in this respect, since the transition multipolarities corresponding to particular allowed values of J involve, in some cases, significant quadrupole or octupole admixtures which would imply measureable Doppler-shift attenuations.

An example of this is the 4.65-MeV level. The χ^2 analyses of the angular-correlation data provide a rigorous restriction of the initial-state spin to values $J_A=3$, 4, 5, or 6, assuming the spin-parity of the 1.13-MeV final state is 5^+. However, the $4.65\rightarrow1.13$ transition must have significant admixtures of octupole radiation if $J_A=3$, or of quadrupole radiation if $J_A=5$. Similarly, the $4.65\rightarrow0.94$ transition must have $L\geqslant2$ for $J_A=5$, or $L\geqslant3$ for $J_A=6$.

It has been suggested previously,[7,14] that the 4.65-MeV level is the $J^\pi=4^+$, $T=1$ analog of the 3.55-MeV level of O^{18} which is known to have $J^\pi=4^+$. This assignment would certainly fit well with the experimentally observed properties of the 4.65-MeV level. However, the 4.40-MeV level presently remains as a candidate for the $J^\pi=4^+$, $T=1$ assignment.

Also included in Fig. 11 are the analog state identifications suggested previously,[7,15] for the F^{18} 4.96- and 4.74-MeV levels. These two levels were not investigated in the present experiment. However, it has been reported by Gorodetzky *et al.*[7] that the 4.74-MeV level decays to the ground state by a transition whose measured correlation is approximately isotropic, in agreement with the 0^+, $T=1$ assignment suggested by Ollerhead *et al.*[15] They also identify a ground-state transition from the 4.96-MeV level, which is consistent with the tentative assignment of $J^\pi=2^+$, $T=1$ suggested previously.[15]

ACKNOWLEDGMENTS

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[14] J. W. Olness and E. K. Warburton, Bull. Am. Phys. Soc. **11**, 405 (1966).

[15] R. W. Ollerhead, J. S. Lopes, A. R. Poletti, M. F. Thomas, and E. K. Warburton, Nucl. Phys. **66**, 161 (1965).