Angular-Correlation Studies of the Reactions $O^{16}(He^3,p\gamma)F^{18}$ and $O^{16}(He^3,\alpha\gamma)O^{15}$

S. Gorodetzky, R. M. Freeman, A. Gallmann, F. Haas, and B. Heusch
Institut de Recherches Nucléaires, Strasbourg, France
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The properties of some bound and nearly bound states of F^{18}, excited in the reaction $O^{16}(He^3,p\gamma)F^{18}$, have been studied by particle-gamma coincidence experiments. Angular correlations of the decay gamma rays, in coincidence with protons detected at angles close to 180° in an annular counter, were measured for three bombarding energies: 4.69, 4.84, and 5.26 MeV. Strong correlations associated with the 2.10-MeV level were observed for 5.26-MeV He^3 energy, enabling it to be shown that the 2.10 MeV $\rightarrow$ 0 transition is almost pure dipole, and to be confirmed that the 1.08-MeV level has spin zero. Results have been obtained for 12 levels of F^{18}, from 3.72- to 5.29-MeV excitation energy, which had previously been little studied. Gamma-ray decay schemes have been given for all these levels, and in many cases limits have been placed on their spins from the angular-correlation results. The 3.72- and 4.84-MeV levels have been assigned $J=1$. Further experimental support was found for the suggestion that the 4.65- 4.74-, and 4.96-MeV levels are the analog states of the 3.55-, 3.63-, and 3.92-MeV levels of O^{18}. Among the unbound levels, no evidence was found for alpha-particle emission competing with the gamma-ray decay, except for the 5.29-MeV level, the highest level studied. Some additional results are also given for the 5.19–5.24-MeV doublet of O^{15} excited in the reaction $O^{16}(He^3,\alpha\gamma)O^{15}$.

I. INTRODUCTION

A LARGE amount of experimental data is now available on the levels of F^{18} up to an excitation energy of 3.5 MeV. Information on these levels is to be found in the article by Poletti and Warburton,[1] where previous experimental work has been summarized. Since this article, new experimental data for these levels have been reported, and further spin and parity assignments have been possible. In particular, the 1.08- and 2.10-MeV levels have been found to have $J=0$ and 2 respectively,[2,3] the 3.06-MeV level has been found[3,4] to have $J^\pi=2^+$ in agreement with the analog level of O^{18}, and the parity of the 3.35-MeV level has been shown to be positive.[3]

Very little is known of the higher lying levels of F^{18} until above 5.5-MeV excitation energy, where it becomes possible to study them by the $N^{14}+\alpha$ reactions. In the intermediate region (3.5–5.5 MeV), the excitation energies of 13 levels have been measured by Hinds and Middleton.[5] When the present experiments were begun, the only gamma-ray transition and spin assignments for these levels have been a possible ground-state transition[6,7] with a large A_4 term, showing it has $J\geqslant 2$, from the 3.84-MeV level, and tentative identification[8] of the 4.65-, 4.74- and 4.96-MeV levels as the analog levels of the second, third, and fourth excited states of O^{18}, with spins and parities 4^+, 0^+, and 2^+, respectively.

[1] A. R. Poletti and E. K. Warburton, Phys. Rev. **137**, B595 (1965).
[2] P. R. Chagnon, Nucl. Phys. **81**, 433 (1966).
[3] J. W. Olness and E. K. Warburton, Phys. Rev. **151**, 792 (1966).
[4] G. M. Matous, G. H. Herling, and E. A. Wolicki, Bull. Am. Phys. Soc. **11**, 333 (1966).
[5] S. Hinds and R. Middleton, Proc. Phys. Soc. (London) **73**, 721 (1959).
[6] E. K. Warburton, J. W. Olness, and D. E. Alburger, Phys. Rev. **140**, B1202 (1965).
[7] K. L. Dunning and J. W. Butler, Phys. Rev. **123**, 1321 (1961).
[8] R. W. Ollerhead, J. S. Lopes, A. R. Poletti, M. F. Thomas, and E. K. Warburton, Nucl. Phys. **66**, 161 (1965).

The present series of experiments was undertaken to study the levels of F^{18} above an excitation energy of 3.5 MeV, and also to obtain, if possible, further data on the lower lying levels. The levels were studied by particle-gamma angular correlation measurements of the reaction $O^{16}(He^3,p\gamma)F^{18}$, where the particles were detected close to 180°, as for method II of Litherland and Ferguson.[9] It is possible to observe particle-gamma coincidences up to an excitation energy of approximately 5.5 MeV in F^{18}, where the levels begin to decay predominantly by alpha-particle emission. Concurrently, similar experiments on the same reaction have been performed at Brookhaven National Laboratory.[10]

A few results for the competing reaction $O^{16}(He^3,\alpha\gamma)O^{15}$ will also be reported.

II. EXPERIMENTAL PROCEDURE

Experimental details of the angular correlation measurements have already been given in preceding articles.[11,12] Some improvements however were made before beginning the present series of measurements. The chamber has been redesigned using the principle described by Olness and Warburton,[3] where the beam is stopped in a Faraday cup located within the chamber. In this way it is possible to make measurements of the gamma-ray intensities at 0° to the beam direction, though for angles less than 30° there was an attenuation of the gamma-ray intensity because of absorption in the materials of the Faraday cup. At 0° the gamma-ray attenuation was measured to be 8% for a cobalt source. Corrections, depending on the gamma-ray energies,

[9] A. E. Litherland and A. J. Ferguson, Can. J. Phys. **39**, 788 (1961).
[10] J. W. Olness and E. K. Warburton, Bull. Am. Phys. Soc. **11**, 405 (1966); and private communication.
[11] S. Gorodetzky, R. M. Freeman, A. Gallmann, and F. Haas, Phys. Rev. **149**, 801 (1966).
[12] A. Gallmann, F. Haas, and N. Balaux, Phys. Rev. **151**, 735 (1966).

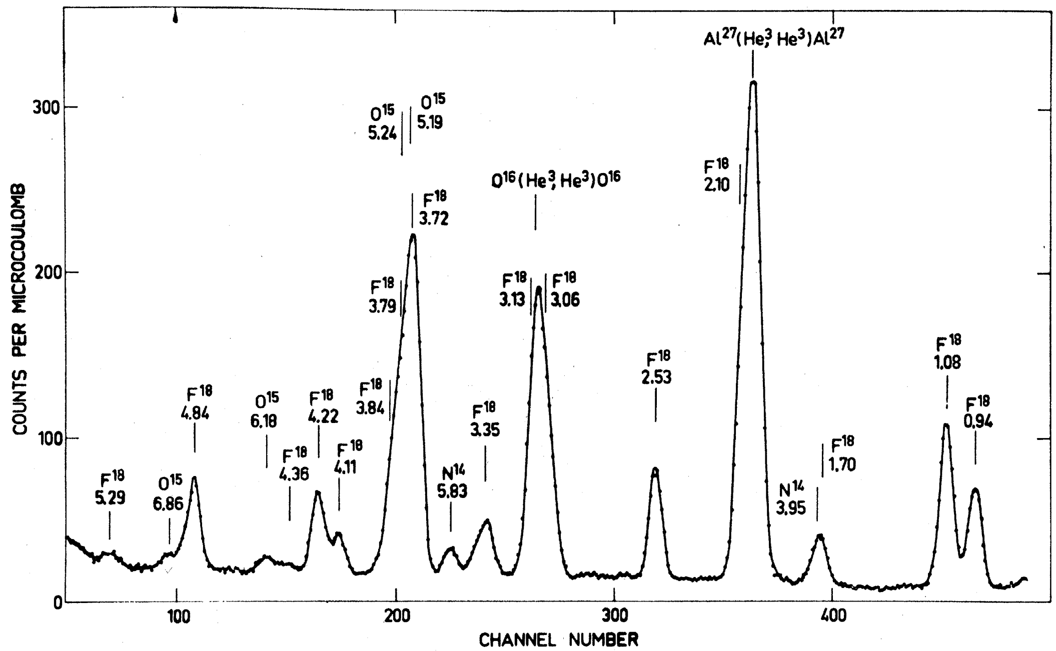

FIG. 1. Particle spectrum for He^3 incident on an Al_2O_3 target at a bombarding energy of 5.25 MeV. Many of the particle groups are labeled by the excitation energy (MeV) and nature of the final nucleus. The peaks are due mainly to elastic scattering and the O^{16}-$(He^3,p)F^{18}$ and $O^{16}(He^3,\alpha)O^{15}$ reactions, but some peaks from carbon impurity, i.e., the reaction $C^{12}(He,p)N^{14}$, are also present.

were applied to all measurements at angles less than 30°.

As in our previous experiments, the particles were detected close to 180° in an annular semiconductor counter placed at 4 cm from the target. The gamma rays were detected in a 5×6-in. NaI crystal, whose front face was 28.5 cm distant from the target. The particle-gamma coincidences were registered in a multidimensional 20 000-channel analyzer (200 channels for the gamma-ray spectra and 100 channels for the particle spectra).

The experiments were repeated for three different He^3 bombarding energies and the coincidence spectra were measured twice at each of five angles: 0°, 30°, 45°, 60°, and 90°. As a first step in the analysis, all ten coincident spectra were added together, in order to have good statistics to determine the gamma-ray decay schemes of the levels. The gamma-ray spectra, shown in this article, were obtained by this means.

The angular correlations from the $O^{16}(He^3,p\gamma)F^{18}$ reaction depend on population parameters describing the relative populations of the $|m|=1$ and 0 magnetic substates. The experimental correlations have been analyzed using the minimum χ^2 computer program previously described.[11] The sign convention adopted for the mixing ratio was that of Litherland and Ferguson.[9] It will be assumed, where the parity change is not known, that the sign is correct for one of the usual mixtures, i.e., $E2/M1$, $E3/M2$, etc. The finite-size effect of the particle counter, arising because the outgoing particles are not detected at 180° but at a mean angle close to 170°, has been considered by allowing a small population of the $|m|=2$ substates, i.e., $P(2)=0.05$.

The targets used in these experiments were thin films of aluminum oxide Al_2O_3, about 60 $\mu g/cm^2$ thick. Some gamma rays from reactions in the aluminum were observed in the coincidence spectra, notably 1.77-MeV gamma rays from the first excited state of Si^{28} formed in the reactions $Al^{27}(He^3,d\gamma)Si^{28}$ and $Al^{27}(He^3,pn\gamma)Si^{28}$, which were in coincidence with particles in the whole range of energies studied. A particle spectrum from the

TABLE I. Summary of the angular-correlation data.

Level of F^{18} (MeV)	He^3 energy (MeV)	Gamma-ray energy (MeV)	Legendre polynomial analysis a_2	a_4
1.08(+1.04)	5.26	1.08(+1.04)	0.00±0.03	0.00±0.03
3.35	4.69	3.35	+0.23±0.09	−0.05±0.10
		1.65+1.70	+0.34±0.09	−0.15±0.09
		0.66	−0.32±0.10	
3.72	4.69	2.68	−0.67±0.06	+0.06±0.06
		1.04	+0.00±0.03	+0.03±0.03
3.79	5.26	1.69	−0.19±0.09	+0.08±0.10
3.84	4.69	3.84	+0.30±0.10	−0.34±0.11
	4.84	3.84	+0.49±0.11	−0.59±0.11
4.11	5.26	1.05	−0.21±0.06	+0.01±0.06
		0.94	+0.30±0.07	+0.00±0.07
4.22	5.26	4.22	−0.45±0.06	+0.15±0.06
		3.28	−0.19±0.07	−0.02±0.07
		0.94	+0.18±0.04	−0.03±0.05
4.36	4.84	1.30	+0.11±0.10	+0.05±0.10
4.65	4.84	3.53	−0.20±0.08	+0.05±0.08
	5.26	3.53	−0.28±0.08	+0.04±0.08
4.74	5.26	4.74	−0.03±0.07	+0.02±0.07
4.84	5.26	3.80	+0.04±0.05	+0.01±0.05
		1.78	+0.03±0.06	+0.01±0.06
O^{15}				
5.19–5.24	4.69	5.19+5.24	+0.33±0.03	−0.59±0.03
	4.84	5.19+5.24	+0.15±0.03	−0.27±0.03
	5.26	5.19+5.24	−0.01±0.03	−0.05±0.03

TABLE II. Summary of the experimental results.

He^3 energy (MeV)	Level of F^{18} (MeV)	Decay transition (MeV)	Branching ratio (%)	Assumed spins and parities $J_i^{\pi_i}$	$J_f^{\pi_f}$	Multipolarities (assumed)	Mixing ratio	Minimum χ^2
5.26	2.10	$2.10\to0$	33±3	2^-	1^+	$E1+M2$	$+(0.025_{-0.12}^{+0.05})$	0.7
		$2.10\to0.94$	33±3	2^-	3^+	$E1+M2$	-0.03 ± 0.15	1.0
		$2.10\to1.08$	34±3	2^-	0^-	$E2$		0.2
		$1.08\to0$		0^-	1^+	$E1$		0.6
4.69	3.35	$3.35\to0$		2^+	1^+	$M1+E2$	$-0.27\geq\delta\geq-0.76$	1.1
							or $\delta\geq+10$ or $\delta\leq-5$	1.1
				3^+	1^+	$E2+M3$	$-(0.12_{-0.13}^{+0.18})$	1.3
		$3.35\to1.70$		2^+	1^+	$M1+E2$	$-0.36\geq\delta\geq-0.80$	1.1
				3^+	1^+	$E2+M3$	$+0.48\geq\delta\geq-0.22$	0.5
4.69	3.72	$3.72\to0$	6±2		1^+			
		$3.72\to1.04$	94±2	1	0^+	$E1$ or $M1$		1.0
5.26	3.79	$3.79\to2.10$		0	2^-			1.0
				1	2^-	$M1+E2$	All values possible	0.2
				2	2^-	$M1+E2$	$+(0.47_{-0.17}^{+0.33})$	0.7
				3	2^-	$M1+E2$	$-(0.10_{-0.12}^{+0.07})$	0.2
							or $\delta\geq+3.0$	0.1
4.84	3.84	$3.84\to0$	39±6	2^+	1^+	$M1+E2$	$-1.9\geq\delta\geq-5.0$	3.7
				3^+	1^+	$E2+M3$	-0.06 ± 0.06	3.8
		$3.84\to3.06$	61±6					
5.26	4.11	$4.11\to0$	<7		1^+			
		$4.11\to1.04$	<10		0^+			
		$4.11\to3.06$	100	1	2^+	$M1+E2$	$-(0.09_{-0.08}^{+0.12})$	0.9
				2	2^+	$M1+E2$	$+0.48\pm0.10$	1.9
				3	2^+	$M1+E2$	-0.06 ± 0.06	0.9
5.26	4.22	$4.22\to0$	32±5	1	1^+	$M1+E2$	Large regions possible	3.3
				2	1^+	$M1+E2$	$+0.25\geq\delta\geq-0.09$	3.3
							or $+(2.25_{-0.75}^{+0.30})$	1.0
		$4.22\to0.94$	55±5	1	3^+	$M2+E3$	All values possible	0.1
				2	3^+	$M1+E2$	$+0.03\geq\delta\geq-0.55$	0.1
							or $\delta\geq+5.0$ or $\delta\leq-3.5$	0.1
		$4.22\to2.10$	13±5		2^-			
4.84	4.36	$4.36\to0.94$	<20		3^+			
		$4.36\to3.06$	(100)	2	2^+	$M1+E2$	$+0.40\geq\delta\geq-0.36$	0.5
							or $\delta\leq-2.5$	0.4
				3	3^+	$M1+E2$	$-0.16\geq\delta\geq-0.42$	0.4
							or $\delta\geq+10.0$ or $\delta\leq-6.0$	0.4
4.84	4.40	$4.40\to0.94$	<40		3^+			
		$4.40\to1.12$	(100)		(5^+)			
4.84	4.65	$4.65\to0.94$	<20		3^+			
+5.26		$4.65\to1.12$	(100)	4	5^+	$M1+E2$	-0.04 ± 0.07	1.3
				6	5^+	$M1+E2$	-0.04 ± 0.04	1.3
5.26	4.74	$4.74\to0$	(100)		1^+			
5.26	4.84	$4.84\to0$	<6		1^+			
		$4.84\to1.04$	65±4	1	0^+	$M1$ or $E1$		0.9
		$4.84\to3.06$	35±4	1	2^+			
4.84	4.96	$4.96\to0$	(100)		1^+			
5.26	5.29	$5.29\to2.53$	(100)		2^+			
	O^{15}							
4.69	5.24	$5.24\to0$	100	$\frac{5}{2}^+$	$\frac{1}{2}^-$	$M2+E3$	$+(0.16_{-0.04}^{+0.11})$	0.6
							or $+2.0\geq\delta\geq+1.4$	0.6

annular detector is shown in Fig. 1. Many of the particle groups from the reactions $O^{16}(He^3,p)F^{18}$ and $O^{16}(He^3,\alpha)O^{15}$, as well as the elastically scattered He^3 particles on the aluminum and oxygen nuclei, have been identified and labeled. Other particle groups with weak intensity have not been indicated. Some peaks from the reaction $C^{12}(He^3,p)N^{14}$, due to carbon impurity in the target, are also evident.

The spectrum shown in Fig. 1, was one of several recorded for He^3 bombarding energies between 4.5 MeV and 5.5 MeV, before deciding on the energies for the angular-correlation experiments. The first energy, 4.69 MeV, was chosen since the relative intensities of some of the particle groups were already known[13] from experiments using a 180° magnetic spectrometer. The second energy, 5.26 MeV, was chosen primarily because the 4.84-MeV level of F^{18} was relatively strongly excited at this bombarding energy. For the third experiment, the angular correlations were studied at a He^3 energy of 4.84 MeV, where the relative intensities of the particle groups were considerably different from those of the first two experiments. For all the experiments, the intensity of the He^3 beam was approximately 0.1 μA, and the measurements at each angle were of the order of two hours duration.

III. EXPERIMENTAL RESULTS

Most of the experimental results have been summarized in Tables I and II. In Table I, the experimental results for the angular correlations have been given,

[13] T. E. Young, G. C. Phillips, R. R. Spencer, and D. A. A. S. N. Rao, Phys. Rev. 116, 962 (1959).

TABLE III. Characteristics of the angular correlations for the 2.10-MeV level of F^{18}.

Gamma-ray energy (MeV)		First run	Second run	Mean
0.94				
	A_0	1.01±0.07	0.90±0.07	0.96±0.05
	A_2/A_0	+0.31±0.12	+0.31±0.13	+0.31±0.09
	A_4/A_0	+0.06±0.13	+0.01±0.15	+0.04±0.10
1.02				
	A_0	0.96±0.07	1.06±0.07	1.01±0.05
	A_2/A_0	+0.63±0.14	+0.59±0.13	+0.61±0.10
	A_4/A_0	−1.10±0.17	−1.11±0.16	−1.11±0.12
1.08				
	A_0	1.09±0.07	0.92±0.07	1.01±0.05
	A_2/A_0	−0.13±0.12	−0.10±0.14	−0.12±0.09
	A_4/A_0	+0.01±0.13	+0.17±0.15	+0.08±0.10
1.16				
	A_0	0.98±0.08	0.96±0.08	0.97±0.06
	A_2/A_0	−0.12±0.14	−0.01±0.14	−0.06±0.10
	A_4/A_0	−0.01±0.15	−0.11±0.15	−0.06±0.11
2.10				
	A_0	0.98±0.08	0.97±0.08	0.98±0.08
	A_2/A_0	−0.41±0.09	−0.46±0.09	−0.43±0.06
	A_4/A_0	+0.06±0.09	+0.13±0.09	+0.09±0.06

where the angular correlations have been fitted by a minimum χ^2 calculation to a series of Legendre polynomials of the form

$$W(\theta)=a_0[1+a_2P_2(\cos\theta)+a_4P_4(\cos\theta)].$$

The coefficients of the Legendre polynomials have not been corrected for the finite size of the NaI crystal. The appropriate attenuation coefficients are $Q_2=0.97$ and $Q_4=0.91$. The results for the 2.10-MeV level, which were subject to a special analysis, will be given in Table III. In Table II, the measured branching ratios, and many of the combinations of spins and mixing ratios which fitted the experimental angular correlations, are listed. The minimum χ^2 value refers, where appropriate, to the analysis in which the mixing ratio was determined. The errors on the mixing ratios are given to one standard deviation and include, where necessary, uncertainties due to the finite size of the particle counter.

The 1.08-MeV Level

When the present experiments were begun, the 1.08-MeV level was the lowest state of F^{18} for which the spin and parity had not been determined, though the spin was known to be limited to the values $J\leqslant 2$. We have therefore studied the correlation between protons to the 1.08-MeV level and the ground-state transition, in an attempt to detect any evidence for a departure from isotropy, which would weigh against the $J=0$ possibility. The experimental correlations will contain an isotropic contribution from the 1.04-MeV ($J=0$) level, which was not resolved from the 1.08-MeV level in either the particle or gamma-ray spectra. At 5.26-MeV He^3 energy, however, the 1.08-MeV level appeared much more intensely in the two dimensional spectra than the 1.04-MeV level. The correlation was therefore determined for this bombarding energy, but no measurable anisotropy was observed, as can be seen from the coefficients given in Table I.

In view of the isotropy of the correlations, which have always been observed for this state, it appears likely that the 1.08-MeV level has $J=0$, though $J=1$ or 2 are not ruled out. Chagnon[2] has recently been able to assign $J=0$ to the state after a study of the $2.10\rightarrow 1.08$ MeV transition. We shall return to a fuller discussion of the 1.08-MeV level in the next section dealing with the 2.10-MeV level, where we have been able to confirm this spin assignment.

The 2.10-MeV Level

The 2.10-MeV level has been recently shown[2,3] to have $J=2$. It decays, with approximately equal probabilities, to the ground state and to the 0.94- and 1.08-MeV levels. The energies of the gamma rays of the cascades, 0.94, 1.02, 1.08, and 1.16 MeV, are poorly resolved in the NaI crystal spectra. The decay scheme has been confirmed using a lithium-drifted germanium detector,[14] and an upper limit of 6% placed on the branch to the 1.04-MeV level. The upper limit has been reduced to 3% in more recent work.[3]

It was noticed in the present experiments that the correlations for the transitions from the 2.10-MeV level were unusually strong at a He^3 energy of 5.26 MeV. For gamma-ray energies in the region of 1 MeV the coincident gamma-ray spectra changed very rapidly with angle. These correlations were first investigated, channel by channel, for gamma-ray energies between 0.7 and 1.3 MeV. The random coincidences were first estimated and subtracted from the spectra. The randoms were more important than usual, because the proton group to the 2.10-MeV level nearly coincided in energy with the He^3 particles scattered elastically from the aluminum of the target (see Fig. 1). The spectra were then adjusted so that there was no relative displacement of the photopeaks with angle. The maximum displacements were less than half a channel for the photopeaks considered.

Correlations were determined for each channel of the gamma ray spectra, and the results expressed as coefficients of the Legendre polynomials in the unnormalized form

$$W(\theta)=A_0+A_2P_2(\cos\theta)+A_4P_4(\cos\theta).$$

It was chosen to express the results in this manner, in order that subsequently they could be fitted with gamma-ray spectrum shapes. During the experiment, two measurements were made at each angle. The two

[14] C. Chasman, K. W. Jones, R. A. Ristinen, and E. K. Warburton, Phys. Rev. **137**, B1445 (1965).

TABLE IV. Properties of the gamma-ray transitions from the 2.10-MeV level of F^{18}.

Transition (MeV)	Branching ratio (%)	$J_f^{\pi_f}$	Multipolarities	Mixing ratio	Γ_γ (eV)	Weisskopf units
$2.10 \rightarrow 0$	36 ± 2	1^+	$E1(+M2)$	-0.01 ± 0.03	5.5×10^{-5}	$(1.3\pm0.5)\times10^{-5}$
$2.10 \rightarrow 0.94$	31 ± 2	3^+	$E1(+M2)$	$+0.00\pm0.06$	4.8×10^{-5}	$(7\pm2)\times10^{-4}$
$2.10 \rightarrow 1.04$	<3	0^+	$M2$		$<5\times10^{-6}$	<36
$2.10 \rightarrow 1.08$	33 ± 2	0^-	$E2$		5.1×10^{-5}	20 ± 7
$2.10 \rightarrow 1.12$	<3	(5^+)	$(E3)$		$<5\times10^{-6}$	$<8\times10^5$

resulting correlations have been treated independently, to check that the results were reproducible. The values of A_0, A_2, and A_4, obtained for the first run, are shown plotted against channel number, in Fig. 2. Very similar results were obtained for the second run.

The most salient feature of this analysis is the large negative peak in the A_4 values, centered at 1.02 MeV, the energy of the $2.10 \rightarrow 1.08$ MeV transition. The presence of the A_4 terms confirms the $J=2$ assignment to the 2.10-MeV level, and requires that the 1.02-MeV transition should be strongly quadrupole in character.

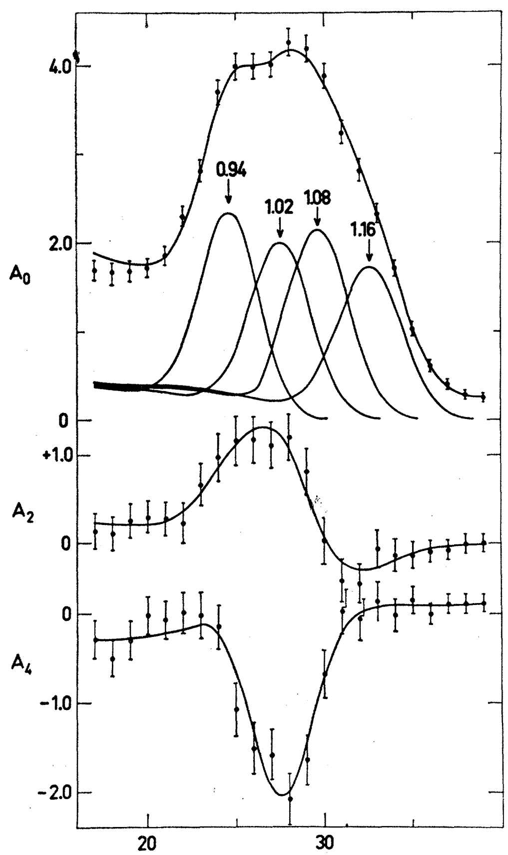

FIG. 2. Experimental A_0, A_2, and A_4 values for the correlations of the decay gamma rays from the 2.10-MeV level of F^{18}. The experimental results were obtained from channel by channel correlations, expressed in the form $A_0+A_2P_2(\cos\theta)+A_4P_4(\cos\theta)$, of the gamma-ray spectra in the region from 0.7 to 1.3 MeV. The fits to the experimental results, using four gamma-ray spectrum shapes plus a constant background, are shown by the full lines. The contribution from each gamma ray is shown for the A_0 values.

To separate the contribution of each individual transition, the A_0, A_2, and A_4 values have been fitted with monoenergetic gamma-ray spectrum shapes, using a minimum χ^2 computer program. The spectrum shapes for all of the four transitions were described by Gaussian distributions, plus additional shapes, to simulate the forms observed experimentally in the region below the photopeaks. The widths of the Gaussians were taken as proportional to $E_i^{1/2}$, where E_i is the energy of the gamma-ray transition. The constant of proportionality was determined from several other gamma rays observed in the two dimensional coincident spectra. The energies of the gamma-ray transitions are accurately known,[14] so the position of the Gaussians could be fixed by a careful energy calibration of the gamma-ray spectra. Only the intensities of the gamma rays were free parameters in the calculation.

The fits of the four gamma-ray shapes plus a supposed constant background to the A_0, A_2, and A_4 values are shown in Fig. 2. With the A_0 values, the contribution from each gamma ray has been represented. The quantitative results of this analysis, as well as the results for the 2.10-MeV transition, are summarized in Table III. The A_0 terms have already been adjusted to correct for the change in efficiency of the NaI crystal with gamma-ray energy. The errors for the A_i terms for the 0.94- and 1.16-MeV transitions of Table III have already been increased by 50%, as these results were found to be very sensitive to a possible error in the gamma-ray energy calibration.

There is very satisfactory agreement between the results of the two runs listed in Table III. Moreover, the two transitions of each cascade agree with each other in intensity. The branching ratios for the 2.10 MeV$\rightarrow$0, the $2.10\rightarrow0.94$ MeV and the $2.10\rightarrow1.08$ MeV transitions were found to be (33 ± 3)%, (33 ± 3)%, and (34 ± 3)%, respectively, in good agreement with previous work, i.e., 42%, 28% and 30% in Ref. 2, and (36 ± 2)%, (31 ± 2)%, and (33 ± 2)% in Ref. 3. The differences between the experimental values come mainly from the measurement of the relative intensity of the 2.10-MeV transition, and are therefore not due to the Gaussian fitting procedure. They may be due to the corrections applied for the change of efficiency with gamma-ray energy for NaI crystals.

We now compare the $a_4(=A_4/A_0)$ values for the angular correlation of the 1.02-MeV transition with those possible theoretically. The initial spin J_i is 2, and for the final spin we will consider the three possibilities for the 1.08-MeV level $J_f=2$, 1 or 0. If $J_f=2$, then the maximum negative value of a_4 possible, including the attenuation coefficient for the finite size of the NaI crystal, is -0.45 (extreme alignment in the $m=0$ substate and pure quadrupole radiation). This is so far from the values observed experimentally that $J=2$ for the 1.08 MeV level can be firmly rejected. If $J_f=1$, then the maximum negative value of a_4 possible is -0.69 (extreme alignment in the $|m|=1$ substates and pure quadrupole radiation). For both runs the experimental values were more than two standard deviations beyond this limit. Thus it is very improbable that the 1.08-MeV state has $J=1$. If $J_f=0$, then the experimental results for the 1.02-MeV transition agree with those predicted theoretically for strong, though not extreme, alignment in the $m=0$ substate.

Having confirmed that consistent results could be obtained from the Gaussian fits, the angular correlations for the 0.94-, 1.02-, 1.08-, and 1.16-MeV transitions were determined by applying the Gaussian fitting procedure to the coincident gamma-ray spectra for each angle. It was first verified that the characteristics of the correlations so obtained were essentially the same as those listed in Table III. Mean correlations were then determined from the two experimental runs. These mean correlations are shown in Fig. 3.

Minimum χ^2 fits to the angular correlation of the 1.02-MeV transition are shown in Fig. 4, for $J_f=0$, 1, and 2, as possible spin assignments for the 1.08-MeV level. For $J=1$ and 2, the χ^2 values always lie above the 0.1% limit, our usual criterion for the rejection of spin values. The 1.08-MeV level is therefore assigned $J=0$, in agreement with the recent work of Chagnon.[2]

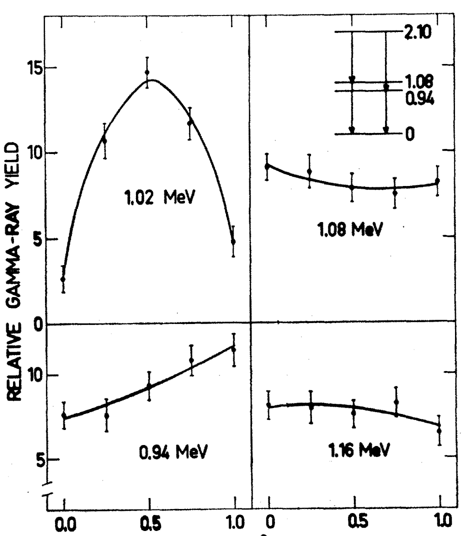

FIG. 3. Correlations for the 0.94-, 1.02-, 1.08-, and 1.16-MeV gamma rays in coincidence with protons to the 2.10-MeV level of F^{18}. Minimum χ^2 fits of the experimental results to a series of Legendre polynomials up to terms in $P_4(\cos\theta)$ are shown by the full lines. The relative intensities are the mean values for the two runs recorded at a He^3 energy of 5.26 MeV.

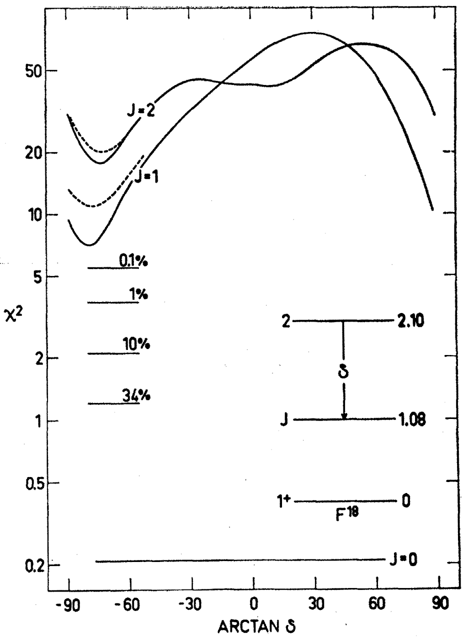

FIG. 4. Analysis of the correlation of the 2.10 → 1.08 MeV transition assuming $J=0$, 1 and 2 successively for the 1.08-MeV level. For $J=1$ and 2 the finite size effect of the particle counter is shown by the dashed lines.

The mixing ratio of the 2.10-MeV transition has been determined by fitting simultaneously the correlations of the 2.10- and 1.02-MeV transitions. As the 1.02-MeV transition is pure quadrupole, its correlation depends only on the alignment. The results of this analysis are shown in Fig. 5. Previously, two solutions for the mixing ratio for the 2.10-MeV transition have been found, one close to zero, the other strongly quadrupole. With the present results, however, it has been possible to rule out the second solution, which would have required a_4 terms in the correlation of the 2.10-MeV transition nearly as large in magnitude as those observed in the correlation of the 1.02-MeV transition. To one standard deviation the mixing ratio δ (sign correct for an $E2/M1$ mixture) was determined to be $-(0.025_{-0.12}^{+0.05})$ and at the 0.1% limit the mixing ratio lies in the range $+0.19\geqslant\delta\geqslant-0.13$. This result is in very good agreement with other experiments which have found that one solution for the mixing ratio is very close to zero.[15]

The mixing ratio of the 2.10 → 0.94 MeV transition has been determined by a simultaneous fit to the correlations of the 1.16- and 0.94-MeV transitions, taking the latter transition to be pure $E2$. The assumption that the $M3$ component of the 0.94-MeV transition

[15] A. R. Poletti, Phys. Rev. **153**, 1108 (1967).

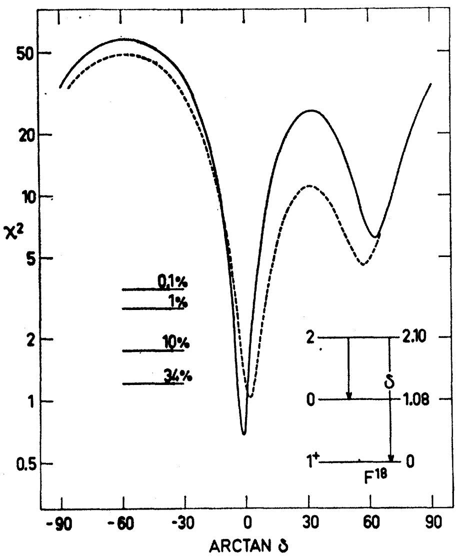

FIG. 5. Determination of the mixing ratio of the 2.10-MeV transition by a minimum χ^2 fit simultaneously to the correlations of the 2.10- and 1.02-MeV transitions. The effect of the finite size of the particle counter is shown by the dashed line.

can be neglected can be justified from the lifetime of the 0.94-MeV level.[3] The population parameter was not a variable in this analysis, but was fixed at the value determined from the correlation of the 1.02-MeV transition. The result of the analysis is shown in Fig. 6. It was verified that the results obtained were not very sensitive to a variation of the population of the $|m|=2$, 1, and 0 substates consistent with the errors of the correlation of the 1.02-MeV transition. The solutions for the mixing ratio for the $2.10 \rightarrow 0.94$ MeV transition are $\delta=+(0.03\pm0.15)$ and $\delta \geqslant +2.6$ (sign correct for an $E2/M1$ mixture) which are in excellent agreement with previous determinations,[15] though it is noted that some allow only the dipole solution.

There is special interest in studying the mixing ratios of the decay gamma rays from the 2.10-MeV level, because the parity of this level had not previously been determined. It is known, however, that the 2.10- and 1.08-MeV levels have the same parity,[3] since only an $E2$ multipolarity could explain the strength of the transition between the two states. There has been a preference for positive parity for the 1.08-MeV level, which was only valid if its spin was 1 or 2, and was based on the significant mixing ratios which would be required to explain the closely isotropic correlations, which have been consistently observed for this level. Once that the 1.08-MeV level was known to have spin zero, the question of its parity was still open. In fact, negative parity assignments for the 1.08- and 2.10-MeV levels would more readily explain the weakness of the quadrupole mixing in the $2.10\text{ MeV} \rightarrow 0$ and $2.10 \rightarrow 0.94$ MeV transitions, as well as the preference of the 2.10-MeV level to decay to the 1.08 MeV rather than the 1.04-MeV level. Decisive evidence in favor of negative parity has been recently found by Poletti,[15] who measured the linear polarization of the 2.10-MeV gamma rays. The polarization measurement, together with the present result that the 2.10-MeV transition is predominantly dipole, are consistent only with an $M2/E1$ mixture for this transition. The 2.10-MeV level, and consequently the 1.08-MeV level also, can therefore be assigned negative parity.

The results of the present experiments are summarized in Table II. The signs have been reversed for the mixing ratio for the 2.10- and the 1.16-MeV transitions from those given in the analyses, as it is now known that both transitions are $M2/E1$ mixtures. The second solution for the mixing ratio in the case of the 1.16-MeV transition, which corresponds to an $M2$ transition strength greater than 200 Weisskopf units, has been dropped. A résumé of the experimental data on the transitions from the 2.10 MeV is given in Table IV, which has been obtained by taking weighted means of the present results with those given in Ref. 2, 3, and 14. The lifetime of the 2.10-MeV level, used to determine the transition strengths, has been taken from Ref. 2. It has been noted that a different sign convention for the mixing ratios has been used in Ref. 3.

The 3.35-MeV Level

The 3.35-MeV level is known to be either a 2^+ or 3^+ state.[3] We have measured angular correlations for the ground-state transition, the two unresolved transitions of the $3.35 \rightarrow 1.70\text{ MeV} \rightarrow 0$ cascade, and for the $1.70 \rightarrow 1.04$ MeV transition, but no new results permitting us to distinguish between the $J=2$ or 3 possibilities have been found.

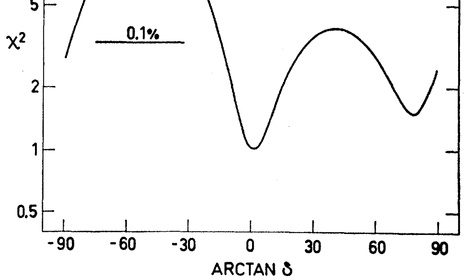

FIG. 6. Determination of the mixing ratio of the $2.10 \rightarrow 0.94$ MeV transition by a minimum χ^2 fit to the correlations of the 1.16- and 0.94-MeV transitions. For this analysis the population parameter was not varied but held fixed at the value calculated from the correlation of the 1.02-MeV transition.

The angular correlations were particularily studied at 4.69-MeV He^3 energy, an energy at which the 5.69-MeV level of N^{14} [formed by the reaction $C^{12}(He^3,p)N^{14}$] was relatively very weakly excited. The 3.38-MeV gamma rays from the 5.69-MeV level seriously interfere with the measurement of the correlation of the 3.35-MeV transition of F^{18}. The results for the three angular correlations measured at this bombarding energy are given in Table I. The values for the mixing ratios deduced for the 3.35- and 1.65-MeV transitions are given in Table II. The mixing ratios for the ground-state transition were obtained by an analysis of the 3.35-MeV transition alone. For the case $J=3$, only one solution was retained in Table II, since from the lifetime measurement[3] the $M3/E2$ mixing ratio should not be significantly different from zero. The mixing ratios for the $3.35\rightarrow 1.70$ MeV transition have been obtained by an analysis involving the angular correlations of the unresolved 1.70- and 1.65-MeV transitions and the 0.66-MeV transition, in a similar manner to that described by Poletti and Warburton.[1]

Though the present results do not lead to accurate values for the mixing ratios, we note two observations in agreement with previous work. Firstly, if $J=2$, then there are important quadrupole components in the $3.35 \text{ MeV}\rightarrow 0$ and $3.35\rightarrow 1.70$ MeV transitions. Secondly, there is no evidence to reject the $J=3$ possibility on the basis that the $M3/E2$ mixing ratios of the 3.35- and 1.65-MeV transitions differ measureably from zero.

The 3.72-MeV Level

The 3.72-MeV level was the first for which there were little experimental data when the present experiments were begun. It proved a relatively easy level to study, partially because its decay was simple (predominantly to the 1.04-MeV level), and also because it was always strongly excited in this reaction. Its decay gamma rays had been observed in earlier experiments, even in targets where oxygen occured only as an impurity, but their origin was not definitely known until the present experiments.

A spectrum of gamma rays, in coincidence with protons to the 3.72-MeV level, is shown in Fig. 7. The gamma rays in coincidence with only one channel of the particle spectrum (the greater part of a proton peak was contained within three channels) have been plotted. This channel was chosen so that there are only a negligible proportion of gamma rays from the neighboring 3.79-MeV level. There are also 5.2-MeV gamma rays present from the 5.19–5.24 MeV doublet of O^{15} excited in the reaction $O^{16}(He^3,\alpha\gamma)O^{15}$. The predominant mode of decay of the 3.72-MeV level is by a 2.68-MeV transition to the 1.04-MeV level. A weak transition to the ground state is detectable by the small peak at 3.72 MeV, which is too large to be a sum peak of the 2.68- and 1.04-MeV gamma rays. The relative intensities of the 2.68- and 3.72-MeV transitions were measured as $(94\pm2)\%$ and $(6\pm2)\%$, respectively. It was noted that there was also the possibility of a 0.66-MeV transition, about 5% the intensity of the 2.68-MeV transition, in the coincident spectra, but it could not be ascertained whether it was due to a transition directly to the 3.06-MeV level, or due to a transition to the 1.70-MeV level, which subsequently decays to the 1.04-MeV level.

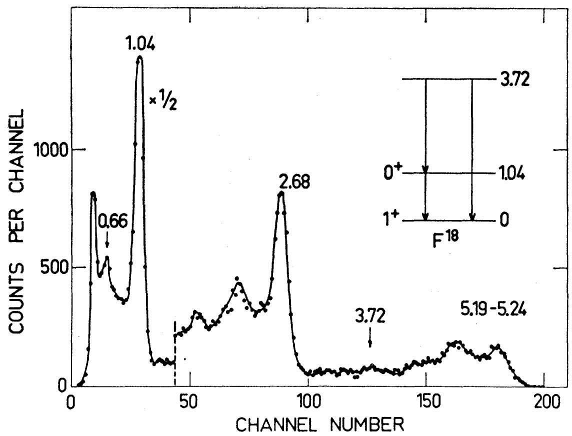

FIG. 7. Spectrum of gamma rays in coincidence with protons to the 3.72-MeV level of F^{18}, obtained at a He^3 energy of 4.84 MeV. The gamma rays observed, whose energies are given in MeV, arise mainly from a cascade through the 1.04-MeV level, though a weak ground-state transition is also observed. The origin of the 0.66-MeV peak is uncertain, and could be due to a transition to either the 3.06- or 1.70-MeV levels. The 5.2-MeV gamma rays are from the 5.19–5.24-MeV doublet of O^{15} excited by the competing reaction $O^{16}(He^3,\alpha\gamma)O^{15}$.

A definite spin assignment for the 3.72-MeV level was possible from the correlation of the 2.68-MeV transition measured at 4.69-MeV He^3 energy (see Tables I and II). At 4.69-MeV bombarding energy it was known that the 3.79-MeV level, which was not well resolved from the 3.72-MeV level in the particle spectrum, was relatively weakly excited.[13] At the other bombarding energies the correlation of the 2.68-MeV transition appeared to be less anisotropic. Only $J=1$ would fit the observed angular correlation for the 2.68-MeV transition; the minimum χ^2 values for other spin possibilities were greater than 100.

The Brookhaven group[10] has also been able to assign $J=1$ to the 3.72-MeV level. Its decay scheme is characteristic of a $J=1$, $T=0$ level, where the dipole transition to the ground state is inhibited by the isotopic-spin selection rule, favoring thus the decay to the $T=1$, 1.04-MeV level.

The 3.79-MeV Level

The 3.79-MeV level was a difficult level to study, being unresolved in the particle spectrum from the 3.72-MeV level on one side and from the 3.84-MeV level on the other. In all experiments, however, there was evidence that 2.1- and 1.7-MeV gamma rays were emitted from the decay of the 3.79-MeV level. It was confirmed that these gamma rays originated from a cascade through the 2.10-MeV and not the 1.70-MeV level, since gamma rays from the $1.70 \rightarrow 1.04$ MeV transition were not seen. There was also fairly strong evidence for a transition to the 3.06-MeV level.

There were sufficient counts from the experiment at 5.26-MeV He^3 energy to study the correlation of the $3.79 \rightarrow 2.10$ MeV transition. It has thus been possible to limit the spin of the 3.79-MeV level to the values $J \leqslant 3$. The mixing ratios, which fitted the correlations for the different spin possibilities, are given in Table II.

The 3.84-MeV Level

The 3.84-MeV level has been found to decay to the ground state and to the 3.06-MeV level. A spectrum of gamma rays, in coincidence with protons to this level, is shown in Fig. 8. There are other gamma rays present which are not associated with the 3.84-MeV level. The 1.69-MeV peak and part of the 2.12-MeV peak are from the decay of the neighboring 3.79-MeV level, and the counts which can be seen above the 3.84-MeV peak are from the 5.19–5.24-MeV doublet of O^{15} excited by the $O^{16}(He^3,\alpha\gamma)O^{15}$ reaction.

Angular correlations have been measured for the ground-state transition, and the results are given in Table I, though it was known that part of the intensity of the 3.84-MeV gamma-rays was due to the 3.90-MeV gamma rays from the 6.21-MeV level of N^{14} excited by the reaction $C^{12}(He^3,p\gamma)N^{14}$. Experimentally, there was evidence that the interference from the 3.90-MeV transition was small, but not negligible. It probably accounts for the poor χ^2 fits to the experimental results, but would not explain the large a_4 terms observed in the angular correlations. It is therefore certain that $J \geqslant 2$. The possibility that $J \leqslant 4$, as well as any significant octupole mixing for $J=3$, can be eliminated by considering the lifetime of the 3.84-MeV level,[3] i.e., <0.073 psec. The only possibilities which remain therefore are $J=2$ or 3. The mixing ratios which fitted the stronger of the two experimental angular correlations are given for both J values in Table II.

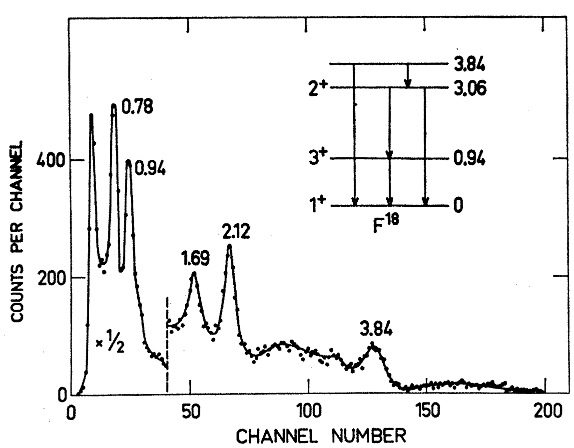

FIG. 8. Spectrum of gamma rays in coincidence with protons to the 3.84-MeV level of F^{18}, obtained at a He^3 energy of 4.69 MeV. The gamma rays observed, whose energies are given in MeV, arise mainly from a transition to the ground state and a cascade through the 3.06-MeV level. Part of the spectrum, notably the peak at 1.69 MeV, is from the decay of the 3.79-MeV level.

It should be possible to decide between $J=2$ and 3 from the angular correlation of the $3.84 \rightarrow 3.06$ MeV transition, since from the lifetime limit, only solutions for the mixing ratio which were predominantly dipole would be acceptable. The measured angular correlations were almost isotropic, implying an important quadrupole mixing for either spin possibility. This apparent contradiction was believed to be due to other gamma rays, unresolved from the 0.78-MeV gamma rays, possibly due to the suspected $3.79 \rightarrow 3.06$ MeV transition. Because of the doubts which exist about the angular correlations for the 0.78-MeV transition their results have not been tabulated.

Using the lifetime limit, it is possible to show that the parity of the 3.84-MeV level is almost certainly positive. If $J=2$, then a conservative limit, $\delta^2 > 0.25$, can be placed on the mixing ratio of the ground state transition. If the parity of the 3.84-MeV level is negative, then the $M2$ transition strength is greater than 8 Weisskopf units, though magnetic multipolarities should be inhibited by the isotopic spin selection rule. In the case $J=3$ the evidence against negative parity is of course even stronger.

The branching ratios were measured as $(39\pm6)\%$ for the ground-state transition and $(61\pm6)\%$ for the $3.84 \rightarrow 3.06$ MeV transition, where the errors include the uncertainties due to the possibility of other unresolved peaks in the gamma-ray spectra. The agreement however is excellent with the values 41% and 59%, respectively, found by the Brookhaven group.[10]

The 4.11-MeV Level

A coincident spectrum of the decay gamma rays from the 4.11-MeV level is shown in Fig. 9. The peaks at 0.94, 1.05, 2.12, and 3.06 MeV all arise from a cascade through the 3.06-MeV state. From the measured intensities of the peaks, there was no reason to believe that the 3.06 and 1.05-MeV gamma rays arose partially because of a cascade through the 1.04-MeV level, and an upper limit of 10% was placed on this possible branch. No other mode of decay was found and an upper limit of 7% was placed on the branching ratio of the ground-state transition. The peak near 1.8 MeV and the counts in the upper part of the spectrum in Fig. 9 come largely from the 8.59-MeV level of Si^{28} excited in the reaction $Al^{27}(He^3,d)Si^{28}$.

All the results for the 4.11-MeV level were obtained for a He^3 energy of 5.26 MeV. It was possible at this energy to determine correlations for the 0.94- and 1.05-MeV transitions by fitting Gaussians to the photopeaks in the manner already described for the 2.10-MeV level. The spectrum shape for the $4.11 \rightarrow 3.06$ MeV transition was fitted best with a Gaussian centered at (1.053 ±0.007) MeV, in excellent agreement with the difference between the excitation energies of the two levels found by Hinds and Middleton.[5]

The results for the two angular correlations are given in Table I. Only for spin values $J=1$, 2, and 3 for the 4.11-MeV level were fits obtained to the correlation of the 1.05-MeV transition. To determine the mixing ratios of this transition corresponding to each assumed spin value, simultaneous fits were made to the angular correlations of the 0.94- and 1.05-MeV transitions. The 0.94-MeV transition was taken as pure quadrupole as in the study of the gamma rays from the decay of the 2.10-MeV level. The angular correlation of the 0.94-MeV transition also depends, though insensitively, on the mixing ratio of the $3.06 \rightarrow 0.94$ MeV transition. This mixing ratio is known experimentally to be small,[3] and the assumption for this analysis, that the transition is pure dipole, could be justified. The minimum χ^2 fits plotted against mixing ratio for the three spin possibilities are shown in Fig. 10. The possible solutions for the mixing ratio of the 1.05-MeV transition are given in Table II.

Although fits to the angular correlations were obtained for $J=1$, 2, and 3, the most likely value of the spin is 3. The decay scheme would be surprising for a $J=1$ level. For $J=2$ the minimum χ^2 value obtained was about 8 times less probable than for $J=1$ or 3. Moreover the mixing ratio required for $J=2$ is unexpected large, considering that in this case ($\Delta T=1$) the dipole component is not inhibited by the isotopic spin selection rule.

The 4.22-MeV Level

Like the 4.11-MeV level, the best results for the 4.22-MeV level were obtained at a He^3 energy of 5.26 MeV.

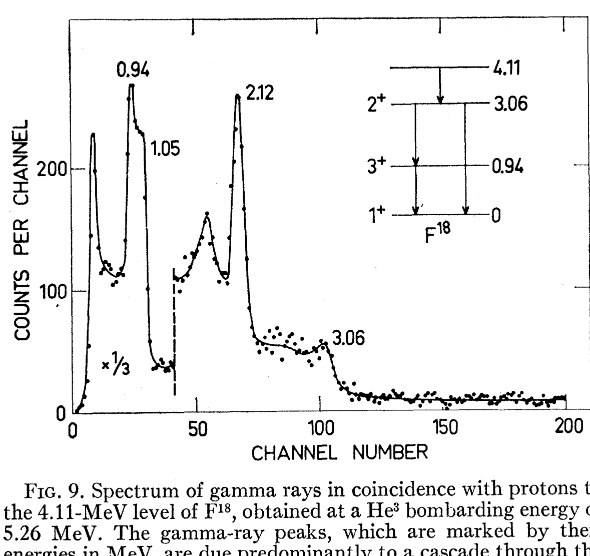

FIG. 9. Spectrum of gamma rays in coincidence with protons to the 4.11-MeV level of F^{18}, obtained at a He^3 bombarding energy of 5.26 MeV. The gamma-ray peaks, which are marked by their energies in MeV, are due predominantly to a cascade through the 3.06-MeV level. The background comes mainly from reactions in the aluminum of the target.

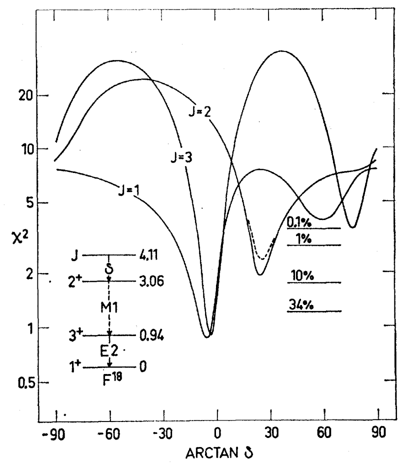

FIG. 10. Simultaneous minimum χ^2 analysis of the 1.05- and 0.94-MeV transitions of the decay of the 4.11-MeV level of F^{18}. The minimum χ^2 values have been calculated for the possible spin assignments to the 4.11-MeV level, $J=1$, 2, or 3, and varying the mixing ratio of the 1.05-MeV transition. The finite size effect of the particle counter is shown by the dashed line in the case of $J=2$.

A spectrum of gamma rays in coincidence with protons to the 4.22-MeV level is shown in Fig. 11. The two most important modes of decay are to the ground state and by a 3.28-MeV transition to the 0.94-MeV level. The peak at 2.12 MeV is a composite peak containing gamma-rays of energy 2.12 and 2.10 MeV from a cascade through the 2.10-MeV level. The possibility that a large portion of the 2.12-MeV peak is due to a cascade through the 3.06 MeV level (the $3.06 \rightarrow 0.94$ MeV transition) can be discounted since there is no evidence for a 1.16-MeV transition of sufficient intensity. Assuming that the decay is by these three branches alone the branching ratios for the 4.22 MeV $\rightarrow 0$, the $4.22 \rightarrow 0.94$ MeV, and the $4.22 \rightarrow 2.10$ MeV transitions were determined to be $(32\pm5)\%$, $(55\pm5)\%$, and $(13\pm5)\%$, respectively. There was however some evidence for other small branches which could not be identified, and we note that while we could not verify a 5% branch through the 1.70-MeV level, reported by the Brookhaven group,[10] a branch less than 10% for this transition is not inconsistent with the present results. The peak at 1.8 MeV is not to be associated with the 4.22-MeV level, but results largely from the excitation of the 8.59-MeV level of Si^{28}, and can be seen also in the spectrum of gamma rays from the 4.11-MeV level (see Fig. 9).

The characteristics of the correlations, determined for the 4.22-, 3.28-, and 0.94-MeV transitions, are listed in Table I. The 0.94-MeV gamma rays are formed in more than one cascade, but the correlation was determined in an attempt to find terms higher than a_2.

Minimum χ^2 fits to the correlation of the 4.22-MeV transition, the transition which showed the most pronounced correlation, are shown in Fig. 12. Only spins $J=1$ and 2 for the 4.22-MeV level lead to fits to the

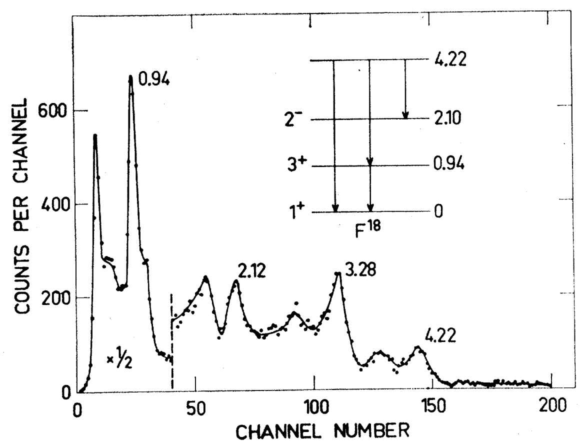

FIG. 11. Spectrum of gamma rays in coincidence with protons to the 4.22-MeV level of F^{18}, obtained at a He^3 bombarding energy of 5.26 MeV. The gamma rays observed, which are indicated by their energies in MeV, are largely due to transitions to the ground state and to the 0.94- and 2.10-MeV levels. The background and the peak near 1.8 MeV come mainly from reactions in the aluminum of the target.

measured angular correlation, and of these, $J=2$ is the more probable. The minimum χ^2 values obtained for $J=1$ are only about 2% probable. The decay scheme also appears more typical of a state with $J=2$ than $J=1$. The only evidence for a measureable a_4 term was in the correlation of the 4.22-MeV transition, but this was not significant enough to allow the $J=1$ assignment to be ruled out.

The measured mixing ratios for the 4.22-MeV transition, and also for the $4.22\rightarrow 0.94$ MeV transition which was analyzed in the same way as the ground-state transition, are given in Table II. For $J=1$ no very useful limits can be placed on the mixing ratios, though the solution $\delta=0$ can be excluded for the 4.22 MeV$\rightarrow 0$ transition.

The 4.36- to 4.40-MeV Doublet

In all three experiments, 1.30-MeV gamma rays, accompanied by 2.12- and 0.94-MeV gamma rays, were seen in coincidence with protons to the 4.36–4.40-MeV doublet. They were identified as gamma rays from the 4.36-MeV level arising from a cascade through the 3.06-MeV level. The identification with the 4.36-MeV level was confirmed for the experiments at 5.26- and 4.84-MeV He^3 energy where gamma rays of weak intensity and 3.28-MeV energy were seen in coincidence at a slightly lower proton energy. The 3.28-MeV gamma rays were due to a cascade from the 4.40-MeV level through the 1.12-MeV level.

A correlation was obtained for the 1.30-MeV transition at a He^3 energy of 4.84 MeV but it was not sufficiently accurate to put any useful restrictions on the spin of the 4.36-MeV level. From the decay scheme the most likely spin of the 4.36-MeV level would appear to be either 2 or 3, and for these two possibilities the mixing ratios measured for the $4.36\rightarrow 3.06$ MeV transition are given in Table II. The Brookhaven group[10] reports that there is a strong branch to the 0.94-MeV level also. We have not found any evidence for a $4.36\rightarrow 0.94$ MeV transition and have placed an upper limit of 20% on this branch in disagreement with their results.

No correlations were obtained for the 4.40-MeV level, but its decay to the 5^+, 1.12-MeV level, suggests that it could be the 4^+, $T=1$, state which is predicted to lie in this region of excitation energies from a comparison with the level scheme of O^{18}. A $4.40\rightarrow 0.94$ MeV transition was also looked for, but the 4.40-MeV level was always weakly excited and it was only possible to put a 40% upper limit on this branch. We shall discuss the 4^+, $T=1$ state again in the next section concerning the 4.65-MeV level.

The 4.65-MeV Level

The 4.65-MeV level was found to decay, like the 4.40-MeV level, to the 1.12-MeV state. Better results were obtained for this level than for the 4.40-MeV state, and angular correlations for the $4.65\rightarrow 1.12$ MeV transition were measured at two bombarding energies (see Table I). In an attempt to determine the spin of the 4.65-MeV level, it was assumed that the decay was to the 1.12-MeV level alone (an upper limit of 20% was placed on the branch to the 0.94-MeV level), and that the spin of the 1.12-MeV level was $J=5$. It was not possible to place useful limits on the spin of the 4.65-MeV level, but it was found that for $J=4$ and 6, there were solutions for the mixing ratio of the $4.65\rightarrow 1.12$ MeV transition which were predominantly dipole. These two solutions only are given in Table II.

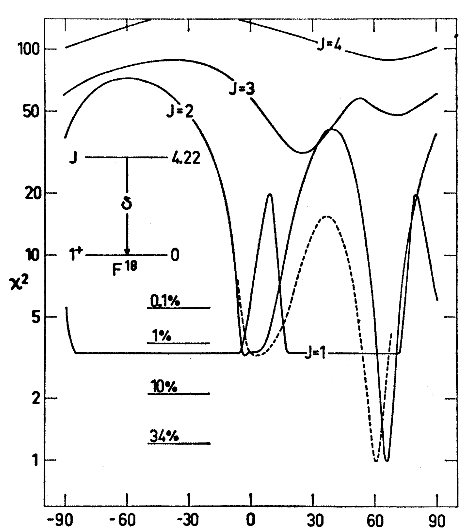

FIG. 12. Minimum χ^2 analysis of the correlation of the 4.22-MeV transition of F^{18}, trying values $J=1$, 2, 3, and 4 for the spin of the 4.22-MeV level. The effect of the finite size of the particle counter is shown by the dashed line in the case of $J=2$.

Olness and Warburton[10] have found a 15% decay to the 3^+, 0.94-MeV level, in which case it is likely that the 4.65-MeV level has $J=4$. The presence of a $4.65 \rightarrow 0.94$ MeV transition, unresolved from the $4.65 \rightarrow 1.12$ MeV transition, will affect the analysis of the correlations and the results given in Table II. If the mixing ratio of the $4.65 \rightarrow 0.94$ MeV transition is small ($|\delta| < 0.1$) then the effect on the solution given for the $J=4$ case will not be very important.

The decay scheme, and the small value measured for the mixing ratio of the $4.65 \rightarrow 1.12$ MeV transition, support the suggestion, originally made by Ollerhead *et al.*,[8] that the 4.65-MeV level is the analog state of the 4^+, 3.55-MeV level of O^{18}. The possibility that the 4.40-MeV level is the 4^+, $T=1$, state should not be overlooked, but the experimental evidence weighs more heavily in favor of the 4.65-MeV level.

The 4.74-MeV Level

The 4.74-MeV level was weakly excited in the present experiments, and for this reason it was not possible to make a very detailed study of its properties. It was found that the level decayed to the ground state, and that the correlation of the resultant 4.74-MeV transition was not measureably different from isotropic. These results agree with, though they do not rigorously confirm, the suggestion[8] that the 4.74-MeV level is the 0^+, $T=1$, state, the analog of the 3.63-MeV level of O^{18}. If this suggestion is correct, then as a consequence of the conservation of parity, the level should not decay by alpha particles. This test could not be usefully applied however, as the 4.74-MeV level is not sufficiently above the $\alpha + N^{14}$ threshold for alpha-particle emission to compete strongly with gamma-ray decay.

The 4.84-MeV Level

Because of the relatively strong excitation of the 4.84-MeV level at a He^3 energy of 5.26 MeV, more accurate results were obtained for this state than for any other in the region above 4.3-MeV excitation energy. A spectrum of gamma rays in coincidence with protons to the 4.84-MeV level is shown in Fig. 13, where the peaks have been identified as due to cascades through the 1.04- and 3.06-MeV levels. There was no evidence for any other mode of decay, and in particular the branch to the ground state was found to be less than 6% of the total gamma-ray decay. The branching ratios for the transitions to the 1.04- and 3.06-MeV states were measured to be $(65 \pm 4)\%$ and $(35 \pm 4)\%$, respectively.

Since the $4.84 \rightarrow 1.04$ MeV transition has pure multipolarity, the spin of the 4.84-MeV can be directly determined from the angular correlation of this transition. The correlation, which is not measureably different from isotropic, as indicated in Table I, was only fitted with a $J=1$ assignment to the 4.84-MeV level. The assignment $J=0$ is not possible because a transition exists to the $J=0$, 1.04-MeV level. Spins greater than 1 could be rejected with a confidence of more than 99.9%. The isotropy of the 3.80-MeV gamma rays can be explained if the m states were approximately equally populated at the bombarding energy for which the angular correlation was measured. In these circumstances, the angular correlations for all the decay gamma rays will be nearly isotropic and a measurement of the mixing ratio of the $4.84 \rightarrow 3.06$ MeV transition is not feasible.

The preference the 4.84-MeV level has to decay to the $T=1$ levels at 1.04 and 3.06 MeV, confirms that the isotopic spin of the level is zero, in agreement with a previous assignment based on its yield in the $Ne^{20}(d,\alpha)F^{18}$ reaction.[16] Moreover the only level of O^{18}, which has the same spin and which could possibly correspond with the 4.84-MeV level, has been associated with states in F^{18}, 800-keV higher in excitation energy.[8] Establishing the $T=0$ nature of the 4.84-MeV level also strengthens the $T=1$ assignments for the surrounding levels at 4.65-, 4.74-, and 4.96-MeV.

Although there was no evidence to suppose that any of the levels below 5-MeV excitation energy decay significantly by alpha-particle emission, the effect was more carefully studied for the 4.84-MeV level, because more accurate results were available for this state, and also because there is no isotopic spin or large angular momentum change to hinder the alpha-particle breakup. An upper limit $\Gamma_\alpha/\Gamma_\gamma \leqslant 0.2$ could be placed on the ratio of the alpha and gamma decay widths.

The 4.96-MeV Level

The 4.96-MeV level was very weakly excited at the bombarding energies chosen and in only one experiment, that at a He^3 energy of 4.84-MeV, were any of its decay gamma rays identified. For this experiment, there was evidence that the level decayed to the ground state. Ollerhead *et al.*[8] have suggested that the 4.96-MeV level is the analog of the 2^+ state at 3.92-MeV excitation energy in O^{18}, but there was no confirmation of this, except that the decay scheme is consistent with this assignment.

The 5.29-MeV Level

The 5.29-MeV level was the highest state studied in the present work and results were only obtained for it at the highest He^3 bombarding energy, i.e., 5.26-MeV. The state appears to decay mainly to the 2.53-MeV level, though there were insufficient counts to analyze the decay scheme accurately. It was verified however, that by adding to the gamma-ray spectrum for the 2.53-MeV level the shape of a 2.76-MeV gamma ray of the

[16] T. Lauritsen and F. Ajzenberg-Selove, *Nuclear Data Sheets*, compiled by K. Way *et al.* (Printing and Publishing Office, National Academy of Sciences—National Research Council, Washington 25, D. C., 1962), NRC 61-5,6-273.

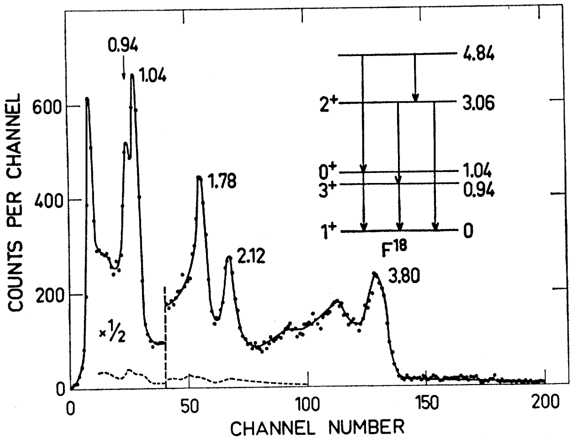

FIG. 13. Spectrum of gamma rays in coincidence with protons to the 4.84-MeV level of F^{18}, obtained at a He^3 bombarding energy of 5.26 MeV. The gamma-ray peaks, which are marked by their energies in MeV, are due to cascades through the 1.04- and 3.06-MeV levels. An estimation of the number of random coincidences is shown by the dashed line.

right intensity, the resulting form agreed with that seen in coincidence with protons to the 5.29-MeV level.

The 5.29-MeV level was the only one studied where the protons feeding the level were found to be only partially in coincidence with gamma rays, i.e., some of the decay is by alpha-particle emission. The ratio of the gamma-ray width (the width for a transition to the 2.53-MeV level alone) to the total width was determined to be $\Gamma_\gamma(2.76\text{ MeV})/\Gamma=0.38\pm0.12$.

IV. THE $O^{16}(He^3,\alpha\gamma)O^{15}$ REACTION

Angular correlations were also measured for the unresolved 5.19–5.24-MeV doublet of O^{15} excited by the reaction $O^{16}(He^3,\alpha\gamma)O^{15}$, and results for all three bombarding energies are given in Table I. For this reaction, the correlations do not depend on population parameters and the differences between the measured angular correlations are due to changes in the relative intensities of the two members of the doublet. The experimental results are consistent with an isotropic correlation for one of the levels, agreeing with the $J=\frac{1}{2}$ assignment to the 5.19-MeV level, and for the 5.24-MeV level ($J=\frac{5}{2}$) a value of either $+(0.16_{-0.04}{}^{+0.11})$ or $+2.0\geqslant\delta\geqslant+1.4$ for the $E3/M2$ mixing ratio of the ground-state transition. Unlike our previous measurement[11] it has been possible, this time, to show that the mixing ratio is definitely positive, since at the 0.1% limit the value lies in one of the ranges $+0.36\geqslant\delta\geqslant0.09$ or $+2.2\geqslant\delta\geqslant+1.2$. The new value $+(0.16_{-0.04}{}^{+0.11})$, though not in disagreement with our earlier value $+(0.035_{-0.04}{}^{+0.11})$, appears to be a more likely result, as it agrees more closely in magnitude with the mixing ratio found by Warburton *et al.*[17] for the analog transition in N^{15} (we consider here only the smaller of the two solutions for the mixing ratio, being the much more probable result).

For the experiment at 4.84-MeV He^3 energy it was possible to verify that the strong correlation was associated with the low-energy side of the alpha-particle peak in the particle spectrum, and the isotropic correlation with the high-energy side, thus confirming that the ordering of the spins in the doublet is $(\frac{1}{2},\frac{5}{2})$ and not the reverse. Confirmation of this point was prompted by the conflict existing between the present results, where a strong correlation was found at 4.69-MeV He^3 energy, and the report[13] that the 5.19-MeV level, whose correlation should be isotropic, is the more strongly excited at this bombarding energy.

V. CONCLUSIONS

The properties of the levels of F^{18} below 3.5-MeV excitation energy are now fairly well known. It remains to show definitely that the 1.12-MeV level has spin and parity 5^+, and to disinguish between the two spin possibilities, $J=2$ or 3, for the 3.35-MeV level. The levels above 3.5-MeV excitation energy have been less studied. Decay gamma rays from 12 of these states were observed in the present experiments. From the angular correlations, limits were placed on the spins of many of the levels, but definite spin assignments could only be made for the 3.72- and 4.84-MeV levels. In Table II a summary of the experimental data is given including the decay schemes of the levels and many of the combinations of spins and mixing ratios which fitted the observed angular correlations.

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[17] E. K. Warburton, J. S. Lopes, R. W. Ollerhead, A. R. Poletti, and M. F. Thomas, Phys. Rev. 138, B104 (1965).