Study of Levels in O^{18} through the Radiative Capture of Alpha Particles by C^{14}

H. E. GOVE AND A. E. LITHERLAND
Chalk River Laboratory, Atomic Energy of Canada Limited, Chalk River, Ontario, Canada

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Two resonances in the reaction $C^{14}(\alpha,\gamma)O^{18}$ have been studied at laboratory alpha-particle energies of 1.142 ± 0.010 and 1.790 ± 0.010 Mev. These correspond to excited states in O^{18} at 7.127 and 7.630 Mev. At the upper resonance only two primary transitions are observed leading to the ground state of O^{18} and the first excited state at 1.98 Mev. Their angular distributions along with other evidence unambiguously establish spins and parities of 1− for the 7.63-Mev state, 2+ for the 1.98-Mev state, and 0+ for the ground state. Values of $\gamma=\Gamma_\alpha\Gamma_\gamma/\Gamma$ of 80 and 160 millielectron volts, respectively, are obtained for the 7.63- and 5.65-Mev $E1$ primary transitions. At the lower resonance again only two primary transitions are observed leading to levels in O^{18} at 1.98 and 3.55 Mev. Greater than 96% of the decays of the 3.55-Mev level lead to the 1.98-Mev level. Analysis of the angular distributions of the four gamma rays observed in the direct spectrum at this resonance, with respect to the incident beam, unambiguously establish spin and parity of 4+ to both the capturing state at 7.13 Mev and the level at 3.55 Mev. Values of γ of 15 and 12 millielectron volts, respectively, are obtained for the 3.58-Mev $M1$ and the 5.15-Mev $E2$ primary transitions. The amount of $E2$ mixing in the former transition is very small.

INTRODUCTION

BECAUSE of its relevance as a test of both the shell and collective models, the nucleus O^{18} has received considerable experimental attention in the last few years in a number of laboratories.[1,2] Recently the elastic scattering of alpha particles in the energy range from 2 to 4 Mev by C^{14} has been investigated[3] at a number of angles. A number of resonances were observed to some of which it was possible to assign spins and parities. Simultaneously with the work reported in this paper Phillips[4] investigated two reasonances in the reaction $C^{14}(\alpha,\gamma)O^{18}$ at alpha-particle energies of 1.794 and 2.334 Mev. He found that both of these gave rise to primary transitions to the ground state and first excited state of O^{18} at 1.98 Mev. Angular-distribution measurements established spins and parities of 1− for the two resonances and, along with other evidence,[2] 2+ and 0+, respectively, to the first excited state and ground state of O^{18}.

The availability of C^{14} targets employed on previous experiments[5] and the considerable work done at Chalk River[6] on F^{18}, the $T_z=0$ member of the isobaric triplet which includes O^{18}, added impetus to the investigation of $C^{14}(\alpha,\gamma)O^{18}$. The spin of 0 for both C^{14} and the alpha particle make it probable that the experimental results will be uniquely interpretable.

[1] K. Ahnlund, Arkiv Fysik **8**, 489 (1954); and Phys. Rev. **96**, 999 (1954); D. R. Bach and P. V. C. Hough, Phys. Rev. **102**, 1341 (1956); N. Jarmie, Phys. Rev. **104**, 1683 (1956).
[2] O. M. Bilaniuk and P. V. C. Hough, Phys. Rev. **108**, 305 (1957).
[3] J. M. Weinman and E. A. Silverstein, Phys. Rev. **111**, 277 (1958).
[4] W. R. Phillips, Phys. Rev. **110**, 1408 (1958).
[5] Bartholomew, Brown, Gove, Litherland, and Paul, Can. J. Phys. **33**, 441 (1955).
[6] Kuehner, Almqvist, and Bromley, Bull. Am. Phys. Soc. Ser. II, **3**, 27 (1958); Almqvist, Bromley, and Kuehner, Bull. Am. Phys. Soc. Ser. II, **3**, 27 (1958); Bromley, Kuehner, and Almqvist, Bull. Am. Phys. Soc. Ser. II, **3**, 27 (1958): (to be published).

EXPERIMENTAL APPARATUS

The alpha-particle beam from the Chalk River Van de Graaff generator stabilized to about 0.1% was focused on an elemental carbon target containing about 25% of C^{14}.[5] The carbon target was deposited on a 0.02-inch thick tantalum backing and beam currents up to about 20 microamperes were employed. The target was about 50 kev thick for 1-Mev protons. For 1.13- and 1.79-Mev alpha particles its thickness can be calculated to be approximately 400 and 500 kev, respectively. As a consequence, in this experiment the target was essentially infinitely thick.

The gamma rays were measured in two 5-inch diameter by 4-inch long NaI(Tl) crystals viewed by 6364 Dumont photomultipliers. After amplification the pulses could be displayed either on a 30-channel pulse amplitude analyzer or a 100-channel transistorized "kicksorter"[7] with automatic print-out. A standard fast-slow coincidence circuit[8] with a resolving time of about 50 millimicroseconds was employed for coincidence measurements. For angular-distribution measurements one crystal was rotated from 0° to 90° to the direction of the incident alpha-particle beam.

EXPERIMENTAL RESULTS

The yield of gamma rays was measured for alpha-particle energies between about 1.3 and 2.0 Mev by recording pulses from one of the detectors in the range corresponding to gamma-ray energies between 3.6 and 7.9 Mev as a function of alpha-particle energy. The results are illustrated in Fig. 1. The absolute energy of the alpha particles was established in another experiment[6] where the $N^{14}(\alpha,\gamma)F^{18}$ reaction was investigated

[7] Designed by F. S. Goulding, Physics Division, Atomic Energy of Canada Limited, Chalk River, Ontario, Canada.
[8] Bell, Graham, and Petch, Can. J. Phys. **30**, 35 (1952).

at a resonance at 1.530 ± 0.003.[9] Of the three resonances observed only that at 1.790 ± 0.010 Mev was due to $C^{14}(\alpha,\gamma)O^{18}$. This resonance has also been observed independently by Phillips[4] at an energy of 1.794 ± 0.006 Mev. Two other resonances were observed at 1.50 and 1.63 Mev. Both the values of the resonance energies and the gamma spectra strongly suggest that they are due to the reaction $B^{10}(\alpha,p\gamma)C^{13}$. It is interesting to note that they were also observed by Phillips.[4]

Since the target was thick it was possible to detect the presence of a lower energy resonance for the reaction $C^{14}(\alpha,\gamma)O^{18}$ by measuring the gamma-ray spectrum below the 1.79-Mev resonance. It was found at an energy of 1.142 ± 0.010 Mev. Figure 1 shows the yield of pulses corresponding to gamma-ray energies between 3.1 and 4.3 Mev in the vicinity of this new resonance.

The rise in gamma-ray yield above the 1.79-Mev resonance is not completely understood. It may be due to the effect of neutrons from the reaction $C^{13}(\alpha,n)O^{16}$ which has been shown[10] to rise rapidly in this region of energy. On the other hand, no step in the yield was observed corresponding to the narrow 1.338-Mev resonance from this reaction. However, since all the measurements to be described were made just below and just above the two steps observed at 1.14 and 1.79 Mev, the effects of other reactions could be essentially eliminated.

The direct gamma-ray pulse spectrum measured at the 1.79-Mev resonance (corresponding to a level in O^{18} at 7.63 Mev) is shown in the upper half of Fig. 2. For this measurement the detector was positioned at 90° to the alpha-particle beam with the front face of the crystal 6.2 inches from the target center. The spectrum was measured just above and just below the rise in the yield at this resonance for the same total charge intercepted by the target. In cases where these two runs

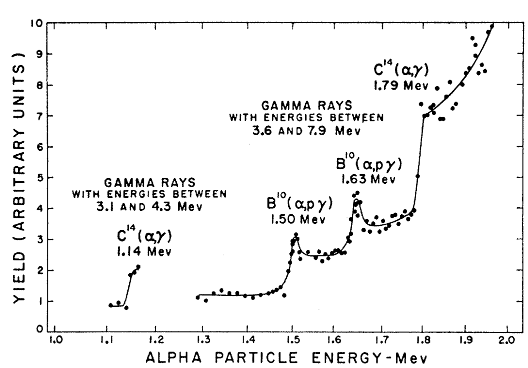

FIG. 1. The yield of gamma rays from the reaction $C^{14}(\alpha\gamma)O^{18}$. For alpha energies between 1.3- and 2.0-Mev voltage pulses from the detector in the range corresponding to gamma-ray energies between 3.6 and 7.9 Mev were recorded. For the lower resonance at $E_\alpha=1.14$ Mev the detector pulses corresponded to gamma rays between 3.1 and 4.3 Mev.

[9] P. C. Price, Proc. Phys. Soc. (London) **48**, 553 (1955).
[10] Walton, Clement, and Boreli, Phys. Rev. **107**, 1065 (1957).

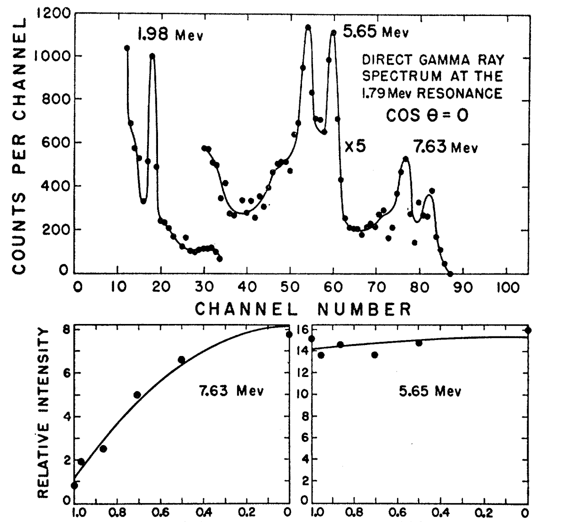

FIG. 2. In the upper half of the figure the direct gamma-ray spectrum measured at the 1.79-Mev resonance in the $C^{14}(\alpha\gamma)O^{18}$ reaction is shown. This resonance corresponds to a level at 7.63 Mev in O^{18}. The two lower curves are the angular distributions of the 7.63- and 5.65-Mev gamma rays with respect to the incident alpha-particle beam.

took different times an appropriate correction was made for gamma-ray background measured with the accelerator turned off. The final spectrum was obtained by subtracting the spectrum measured below the resonance from that measured above. This procedure was followed at a number of angles between the counter and the beam direction from 0° to 90°. At this resonance only three gamma rays are observed with energies of 7.63, 5.65, and 1.98 Mev. Coincidence measurements established the obvious fact that the 1.98- and 5.65-Mev gamma rays were members of a cascade. The 7.63- and 5.65-Mev gamma rays are interpreted as primaries to the ground state and first excited state at 1.98 Mev of O^{18}. There is evidence for a gamma ray with a peak in channel 32 in the spectrum shown in Fig. 2. This corresponds to an energy of about 3.2 Mev. If this were one member of a cascade from this resonance, the other member would have an energy of about 4.4 Mev and would be effectively obscured by the second escape peak of the 5.65-Mev gamma ray. No level is known at 3.2 Mev in O^{18} but the work of Jarmie[1] would not exclude the possibility of a level at 4.4 Mev. On the other hand, a gamma ray of about 3.2 Mev could arise due to imperfect subtraction of the effect of the $B^{10}(\alpha,p\gamma)$ reaction. No such gamma ray was observed by Phillips.[4] He used much smaller NaI(Tl) crystals for gamma-ray detectors and this would make the observation of weak 3-Mev gamma rays somewhat more difficult. From the spectrum measurements as a function of angle the angular distributions of the 7.63- and 5.65-Mev gamma rays were obtained and are shown in the lower half of Fig. 2. They were fitted by the method of least squares to the expression $W(\theta)=a_0+a_2P_2$ on the Chalk River

TABLE I. Coefficients in the expansion $W(\theta)=\Sigma_n a_n P_n(\cos\theta)$ fitted by the method of least squares to the experimentally measured direct correlations.

Resonance energy (Mev)	Gamma ray energy (Mev)	Angular distribution coefficients a_2/a_0[d]	a_4/a_0[e]
1.790	7.63[a]	-0.833 ± 0.116	
	5.65[a]	-0.051 ± 0.044	
1.142	5.15[b]	$+0.511\pm0.075$	-0.350 ± 0.081
	3.58[b]	$+0.411\pm0.053$	-0.071 ± 0.064
	1.98[b, c]	$+0.446\pm0.074$	-0.269 ± 0.089
	1.57[b]	$+0.385\pm0.071$	-0.144 ± 0.088

[a] Here the fit was made to $W(\theta)=a_0+a_2P_2(\cos\theta)$.
[b] Here the fit was made to $W(\theta)=a_0+a_2P_2(\cos\theta)+a_4P_4(\cos\theta)$.
[c] A second measurement of this distribution gave $a_2/a_0=0.414\pm0.099$ and $a_4/a_0=-0.164\pm0.124$.
[d] To correct for finite solid angle, multiply these values by 1.09.
[e] To correct for finite solid angle, multiply these values by 1.33.

Datatron computer and the coefficients are listed in Table I. These coefficients must be corrected for finite solid angle for the geometry employed[11] using the method of Rose.[12,13] When this is done the a_2/a_0 coefficient for the distribution of the 7.63-Mev gamma ray becomes -0.91 ± 0.13. Assuming that C^{14}, O^{18}, and the alpha particle have spin zero and even parity for their ground state, this correlation is consistent only with a spin and parity of 1− for the 7.63-Mev level in O^{18}. For such a case theory predicts $W(\theta)=1-P_2(\cos\theta)$.

With the assignment 1− established for the capturing state at 7.63 Mev, the corrected angular distribution of the gamma-ray transition to the first excited state at 1.98 Mev $[1-(0.056\pm0.048)P_2(\cos\theta)]$ establishes its assignment to be 2+ for which theory predicts $1-0.1P_2(\cos\theta)$. If the 1.98-Mev level were 1+, the angular distribution of the gamma ray transition from the 1− capturing state would be $1+0.5P_2(\cos\theta)$. One cannot rule out the possibility of 1− for the 1.98-Mev level since a suitable $M1$-$E2$ mixture would give rise to the observed distribution, but such an assignment is unlikely. The angular distribution of the 1.98-Mev gamma ray was not measured. It is theoretically expected to be $1+0.5P_2$.

The branching ratio for the 7.63-Mev level is obtained by measuring the total number of pulses in the spectrum of Fig. 2 of magnitude greater than that corresponding to gamma rays of energy $E_\gamma-1.02$ Mev, where E_γ is the energy of the gamma ray in question (in this case the 7.63- and 5.65-Mev primaries). These numbers are then corrected for the corresponding efficiencies employing the curve shown in Fig. 3. These curves were measured[14] using a number of sources of gamma rays both radioactive and induced by (He^3,p) and (p,γ) reactions as indicated by the labels. Finally a correction is made for the measured angular distributions. The resulting branching ratio is 33:67 for the intensity of 7.62- to 5.65-Mev gamma rays. Phillips also obtains this ratio.[4]

The quantity

$$\omega\gamma=\frac{2J+1}{(2I_0+1)(2i+1)}\left(\frac{\Gamma_\alpha\Gamma_\gamma}{\Gamma}\right),$$

where J, I_0, and i are the total angular momentum of the capturing state, the target nucleus, and the incident particle (1, 0, and 0, respectively, in this case), was measured for the ground-state gamma transition by comparing the step in the thick-target yield at this 1.79-Mev resonance with that for the 10.7-Mev ground-state transition in the reaction $C^{14}(p,\gamma)$ at the 0.537-Mev resonance[5] using the same target and experimental arrangement. In the calculation it was assumed that the target was 25% C^{14} and that the stopping power of 1.79-Mev alpha particles was four times the value for protons of one quarter the energy. Taking the latter value from Allison and Warshaw,[15] one obtains 35×10^{-15} ev cm² per atom for 1.78-Mev alpha particles in carbon. The value of $\omega\gamma$ so obtained was 0.24 ev and hence $\gamma=\Gamma_\alpha\Gamma_\gamma/\Gamma=0.08$ ev for the 7.63-Mev gamma transition. The value obtained by Phillips[4] was 0.12 ev. Branching ratios and values of γ for this resonance are given in Table II.

Turning now to the lower energy resonance at 1.14 Mev (corresponding to a level in O^{18} at 7.13 Mev), the direct gamma-ray pulse spectrum using the on-off resonance method described above is shown in the upper

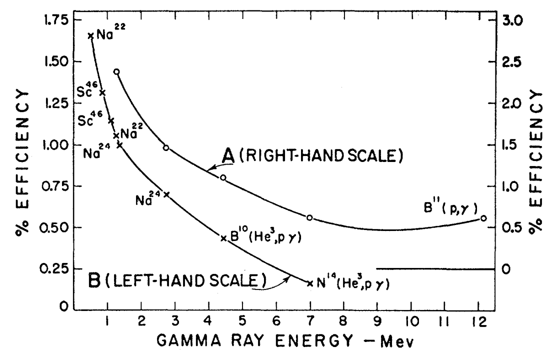

FIG. 3. Percent efficiency as a function of gamma-ray energy for a 5-inch diameter by 4-inch long NaI(Tl) crystal with its front face 6.2 inches from the target center. The upper curve applies when all pulses greater than the voltage corresponding to $E_\gamma-1.02$ Mev are counted. The lower curve applies when only pulses in the total absorption peak are counted. Each point is labelled by the radioisotope or reaction employed to make the efficiency measurement.

[11] H. E. Gove and A. R. Rutledge, Chalk River Report CRP-755, 1958 (unpublished).
[12] M. E. Rose, Phys. Rev. **91**, 610 (1953).
[13] This overestimates the correction because only the highest energy portion of the spectrum was used in the angular distribution.
[14] The measurements were made in collaboration with E. Almqvist, D. A. Bromley, A. J. Ferguson, and J. A. Kuehner. Figure 3 supplants Fig. 2 of A. E. Litherland *et al.*, Phys. Rev. **102**, 208 (1956), which is in error beyond 3 Mev.
[15] S. K. Allison and S. D. Warshaw, Revs. Modern Phys. **25**, 779 (1953). Curves of proton stopping power are contained in the chapter "Resonance Reactions—Experimental", by H. E. Gove of the book *Nuclear Reactions*, edited by M. Demeur and P. M. Endt [North-Holland Publishing Company, Amsterdam (to be published)].

TABLE II. Gamma-ray branching ratios and values of $\gamma=\Gamma_\alpha\Gamma_\gamma/\Gamma$ for levels in O^{18}.

Excitation energy (Mev) Initial state	Final state	Branching ratio (%)	γ (10^{-3} ev)
7.63	0	33	79
	1.98	67	158
7.13	1.98	44	12
	3.55	56	15
3.55	0	< 4	
	1.98	>96	

half of Fig. 4. In this case four gamma rays are observed with energies 5.15, 3.58, 1.98, and 1.57 Mev. No evidence for a direct 7.12-Mev transition to the ground state was observed and an upper limit of about 10% of the 5.15-Mev transition can be set for its intensity. Measurements to be described below established that the 3.58-Mev gamma rays were in coincidence with both the 1.98- and the 1.57-Mev gamma rays. The most reasonable interpretation of these results is that the 5.15- and 3.58-Mev gamma rays are primaries leading to states in O^{18} at 1.98 and 3.55 Mev, respectively. The 3.55-Mev state decays by a cascade through the 1.98-Mev state giving rise to the observed 1.57-Mev gamma ray. One cannot exclude the possibility that the triple cascade involving the 3.58-, 1.57-, and 1.98-Mev gamma rays takes place in some other sequence.

As before, the angular distributions of these four gamma rays with respect to the incident alpha-particle beam were obtained by measuring the direct spectrum on and just below resonance at a series of angles between 0° and 90°. Because the 1.46-Mev gamma ray arising from the decay of K^{40} is a particularly trouble-

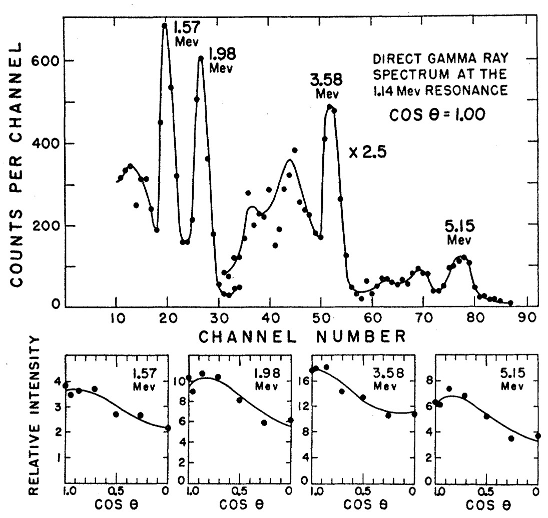

FIG. 4. In the upper half of the figure the direct gamma-ray spectrum measured at the 1.14-Mev resonance in the $C^{14}(\alpha\gamma)O^{18}$ reaction is shown. This resonance corresponds to a level at 7.13 Mev in O^{18}. The four lower curves are the angular distributions with respect to the incident alpha-particle beam of the four gamma rays observed in the direct spectrum.

some background and because it is close enough in energy to the 1.57-Mev gamma ray so that the two are not completely resolved, it was necessary to take special precautions to shield the moving crystal from the concrete walls and ceilings of the target room. Three inches of lead shielding completely surrounded the crystal and a special collimator was added between the target and crystal front face, which, although not changing the solid angle subtended at the source, considerably reduced the area of walls and ceilings viewed directly by the crystal. Despite this, the K^{40} gamma ray was still about equal in intensity to the 1.57-Mev gamma ray on resonance and a rather large off-resonance subtraction was required. Fortunately the angular distribution of the 1.57-Mev gamma ray was in no way crucial to the arguments leading to spin assignments at this resonance. The measured angular distributions are shown in the lower part of Fig. 4 and the coefficients obtained by fitting the data to a Legendre-polynomial distribution by a least-squares procedure are listed in Table I. As indicated in the table, the angular distribution of the 1.98-Mev gamma ray was measured twice and the two sets of coefficients agree within the errors. The errors are obtained assuming equal statistical weights for each point on the angular distribution.

Since the interpretation[16] of these angular distribution results is considerably more involved than for the higher resonance, it will be deferred to the appendix of the paper. In summary, the angular distribution of the 5.15-Mev gamma rays permits the capturing state at 7.13 Mev to be either 4+ or 2+. The angular distribution of the 3.58-Mev gamma rays permits the states at 7.13 and 3.55 Mev to be 4+ and 4+, or 2+ and 2+, or 2+ and 3+. The angular distribution of the 1.57-Mev gamma rays is consistent with any of these three combinations. The angular distribution of the 1.98-Mev gamma rays is consistent only with the first possibility of 4+ for both the 7.13-Mev and 3.55-Mev states in O^{18}. The 5.15-Mev gamma ray transition between the 7.13- and 1.98-Mev states is then pure $E2$ and the 3.58-Mev transition from the 7.13- to the 3.55-Mev level is an $M1$-$E2$ mixture. However, as shown in the appendix the $E2$ to $M1$ amplitude ratio for this latter transition is quite small (-0.04 to -0.14) and hence it is practically pure $M1$. The assignment of 4+ to the 3.55-Mev level is in agreement with the conclusions of Bilaniuk and Hough[2] based on the angular distribution of protons leading to this state from the $O^{17}(d,p)O^{18}$ reaction.

Assuming that the 3.58-Mev gamma ray is a primary leading to the 3.55-Mev level in O^{18}, it was necessary to determine whether this level decayed directly to the ground state. The gamma ray from such a decay is essentially indistinguishable from one of energy 3.58

[16] The authors are indebted to W. T. Sharp, Physics Division, Atomic Energy of Canada Limited, Chalk River, Ontario, Canada for advice on this point. The notation employed is described by Sharp, Kennedy, Sears, and Hoyle, in the Chalk River Report CRT-556, 1954 (unpublished).

Mev and hence would not be revealed in the direct spectrum. For this measurement the two detectors were set with their front faces 6.2 inches from the target center. A voltage window was set to include the pulses in the total absorption and first escape peak of 3.58-Mev gamma rays from one detector (crystal *A*) while the spectrum of pulses in coincidence with these was measured in the other (crystal *B*). The same measurement was made for three different geometries (*A* at 120°, *B* at 90°; *A* at 90°, *B* at 90°; *A* at 90°, *B* at 0°, where the angles for crystal *A* are on one side of the beam and for *B* on the other) in order to average over angular-correlation effects. No measurements were made with one of the detectors moved out of the plane containing the beam axis and the other detector, so that complete averaging was not obtained. The three coincidence spectra were added together and are shown in Fig. 5. As can be seen, there is no evidence for a 3.55-Mev gamma ray and an upper limit on its intensity compared to the 1.57-Mev gamma ray is 4%.

The gamma-ray branching ratio of this 7.13-Mev level in O^{18} was obtained by measuring the total number of pulses in the total absorption peaks of the 5.15- and 3.58-Mev gamma rays of Fig. 4 and then applying corrections for the measured angular distributions and for crystal efficiency. In this case the lower curve of Fig. 3 is used. The branching ratio so obtained is 44:56 for the intensity of the 5.15- to 3.58-Mev gamma rays. As for the higher resonances, values of $\omega\gamma$ were obtained for the two primary gamma transitions for this 1.13-Mev resonance. As will be demonstrated in the appendix, the spin and parity for this resonance is 4+ yielding a value of nine for

$$\omega=\frac{2J+1}{(2I_0+1)(2i+1)},$$

and using this the value obtained for γ for the 5.15- and 3.58-Mev gamma transitions are 12×10^{-3} and 15×10^{-3} ev, respectively. These results are summarized in Table II.

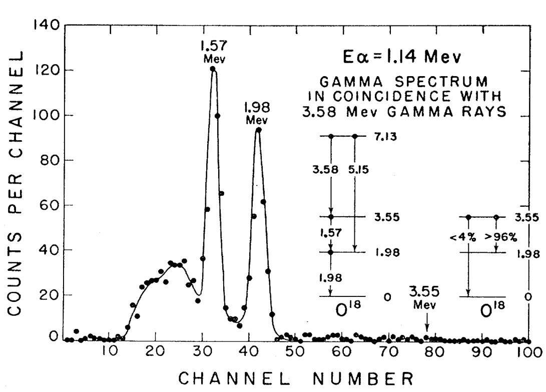

FIG. 5. Gamma-ray spectrum in coincidence with the 3.58 Mev gamma rays of Fig. 4 measured at the 1.14-Mev resonance. The figure insets show the decay scheme. The absence of a crossover gamma ray of 3.55 Mev energy permits the branching ratio shown in the second inset to be established.

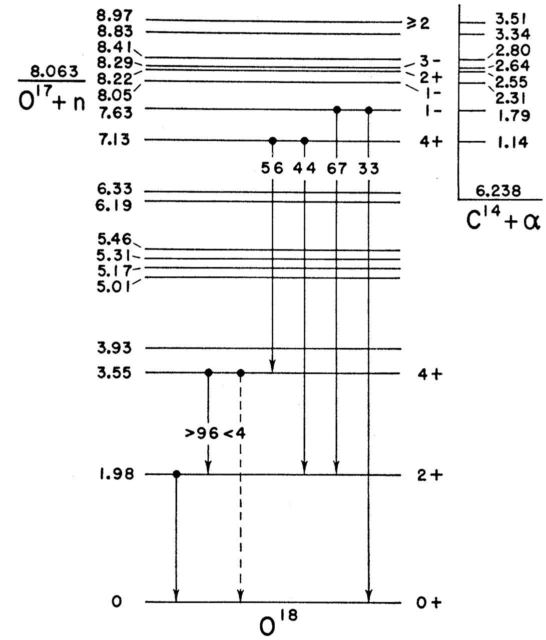

FIG. 6. Energy level diagram of O^{18} showing the gamma rays studied. The gamma-ray branching ratios are shown as well as spin and parity assignments.

DISCUSSION OF TRANSITION PROBABILITIES

The results of the experiments described in this paper are summarized in the energy level diagram shown in Fig. 6. In the one gamma transition shown on this diagram in which an *M*1-*E*2 mixture is possible, namely, the 4+ to 4+ transition of energy 3.58 Mev between the 7.13- and 3.55-Mev levels the amplitude ratio of *E*2 to *M*1 is −0.04 to −0.14 or practically pure *M*1. Hence all the gamma transitions observed are pure multipoles, two being *E*1, one *M*1, and three *E*2. It is of interest to compare the transition probabilities with others found in light nuclei. Such a comparison is greatly facilitated by the recent compilation and interpretation of electromagnetic transitions by Wilkinson.[17]

At the 1− resonance at 1.79 Mev corresponding to a level in O^{18} at 7.63 Mev, two *E*1 transitions are observed leading to the ground and first excited state with values of $\gamma=\Gamma_\alpha\Gamma_\gamma/\Gamma$ equal to 79×10^{-3} and 158×10^{-3} ev, respectively. From arguments given below, it is probably safe to assume that the alpha-particle partial width Γ_α at this resonance considerably exceeds the partial gamma widths Γ_γ. Hence $\gamma=\Gamma_\gamma$ to a good approximation. The ratio of Γ_γ to the *E*1 Weisskopf unit defined by Wilkinson[17] is listed as $|M|^2$ in Table

[17] D. H. Wilkinson, *Proceedings of the Rehovoth Conference on Nuclear Structure,* edited by H. J. Lipkin (North-Holland Publishing Company, Amsterdam, 1958).

TABLE III. Comparison between partial gamma-ray widths in O^{18} and Weisskopf values. $|M|^2$ is the ratio of the observed partial gamma-ray width to the Weisskopf unit as defined by Wilkinson (reference 15). In the last column, Γ_γ is in ev and E_γ in Mev.

Initial state Energy (Mev)	$J\pi$	Final state Energy (Mev)	$J\pi$	$E\gamma$ (Mev)	Type of radiation	$\Gamma\gamma\times10^3$ (ev)	$\|M\|^2$	$\Gamma\gamma/E\gamma^3$
7.63	1−	0	0+	7.63	$E1$	79	2.4×10^{-4}	1.8×10^{-4}
7.63	1−	1.98	2+	5.65	$E1$	158	1.2×10^{-3}	8.8×10^{-4}
7.13	4+	3.55	4+	3.58	$M1$	≥ 15	$\geq1.6\times10^{-2}$	$\geq3.3\times10^{-4}$
7.13	4+	1.98	2+	5.15	$E2$	≥ 12	≥0.59	
7.13	4+	3.55	4+	3.58	$E2$	$\geq0.02\rightarrow0.3$	$\geq7\times10^{-3}\rightarrow9\times10^{-2}$	

III, as well as the value of Γ_γ/E_γ^3, where Γ_γ is in units of electron volts and E_γ in Mev. On the basis of Wilkinson's compilation,[17] he has concluded that if the quantity Γ_γ/E_γ^3 for a dipole transition is less than 4×10^{-4} it is very probably $M1$ unless it is an isotopic-spin-forbidden $E1$. In this case all the levels involved in O^{18} have $T=1$ and the ground-state transition violates the rule. No explanation readily presents itself to account for the slowness of these $E1$ transitions. The other 1− level at 8.05 Mev investigated by Phillips[4] has almost identical transition probabilities to this 7.63-Mev level so that all four of the known $E1$ transitions in O^{18} are considerably slower than other allowed $E1$ transitions in light nuclei.

At the 4+ resonance at 1.14 Mev corresponding to a level in O^{18} at 7.13 Mev, an $E2$ transition and an $M1$-$E2$ mixture which is practically pure $M1$ are observed. In this case it is not possible to conclude that $\Gamma_\alpha\gg\Gamma_\gamma$ since the resonance is formed by g-wave alpha particles. The single-particle limit for this will be discussed below. Hence the measured values of $\gamma=\Gamma_\alpha\Gamma_\gamma/\Gamma$ can only be taken as lower limits to the partial gamma widths and are so listed in Table III. Both $|M|^2$ and Γ_γ/E_γ^3 for the $M1$ transition are consistent with the mean values obtained in light nuclei by Wilkinson.[17] The pure $E2$ transition (4+ to 2+) has $|M|^2\geq0.59$ which is about the average value for $E2$ transitions, indicating some collective enhancement. The $E2$ part of the $M1$-$E2$ mixture ($4+\rightarrow4+$), on the other hand, has $|M|^2\geq7\times10^{-3}$ to 9×10^{-2}, where the two limits correspond to the limits on the $E2$-$M1$ amplitude ratios of −0.04 to −0.14 and is weak by comparison with other $E2$ transitions in this region of atomic weight.

In order to compute reduced widths for alpha particles, some estimate of radius must be made for the interaction between a target nucleus A and an alpha particle. One such estimate can be made from the results of elastic scattering of alpha particles[18] in which the sharp cutoff model of Blair[19] is used to obtain the interaction radius. The radius obtained in this way can be written[18]

$$R_{A\alpha}=(1.414A^{\frac{1}{3}}+2.190)\times10^{-13}\text{ cm},$$

and over a wide range of target elements of atomic number A ranging from Ne to Pu the deviations from this expression are generally less than 1%. For $C^{14}+\alpha$ this gives $R_{A\alpha}=5.6\times10^{-13}$ cm.

If one then defines the single-particle limit as follows:

$$\Gamma_l^{sp}=\frac{\hbar^2}{\mu R_{A\alpha}^2}\frac{2\rho}{A_l^2},$$

where $A_l^2/2\rho$ is related to Coulomb penetrability functions,[20] μ is the reduced mass, and $R_{A\alpha}$ is taken to be 5.6×10^{-13} cm, a value of about 20 kev is obtained for the 1− resonance at 1.79 Mev and 0.57 ev for the 4+ resonance at 1.14 Mev. Hence, even if the total width of the 1− resonance were a small fraction of the single-particle limit, it would still be large compared to the measured total $\gamma=0.237$ ev, and hence it seems reasonable to assume that it is Γ_γ which is being measured. On the other hand, for the 4+ resonance the measured total γ is 0.027 ev and this is only about 20 times smaller than the single-particle limit; hence one can only assume that the ratio of the actual alpha width of this level to the single-particle limit is greater than 0.05. This lower limit corresponds to the average value for allowed alpha transitions compiled by Wilkinson,[17] where an interaction radius of the form

$$R_{A\alpha}=1.45(A^{\frac{1}{3}}+4^{\frac{1}{3}})\times10^{-13}\text{ cm},$$

was employed.[21] This gives a value of 5.8×10^{-13} cm for $C^{14}+\alpha$, which is very close to the value used in these calculations.

Thus the 4+ state at 7.13 Mev in O^{18} is characterized by a width for formation by alpha particles which is equal to or exceeds the average value for allowed alpha transitions in light nuclei and a width for emission of $E2$ radiation to the first excited state of O^{18} which also equals or exceeds the values found for other light nuclei, while the 1− state at 7.63 Mev decays by $E1$ emission with much lower than average probability. The results for the 7.63-Mev state are in agreement with those of Phillips[4] and are almost identical to those he obtained for a higher 1− resonance corresponding to a level in O^{18} at 8.05 Mev.

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COMPARISON WITH NUCLEAR MODELS

The nuclear shell model has been applied to mass-18 nuclei by Redlich[22] and by Elliott and Flowers.[23] Redlich has assumed a scalar Gaussian interaction between the two nucleons outside the O^{16} core, while Elliott and Flowers use a Yukawa potential. In both cases all configurations involving those binary products of $d_{\frac{5}{2}}$, $d_{\frac{3}{2}}$, and $s_{\frac{1}{2}}$ which give the correct J and T for a level are allowed. In neither case do the level positions give particularly good agreement with those observed experimentally in O^{18}. However, Bilaniuk and Hough[2] have obtained rather good agreement between the wave function coefficients predicted by Redlich[22] and the values obtained by extracting reduced stripping widths from the experimental data.

It has been pointed out by Elliott,[24] however, that the introduction of surface particle coupling of a similar magnitude to that required to explain[23] the $E2$ lifetime of the 197-kev level in F^{19} has a rather profound effect on the level spacings in O^{18} while in F^{19} the effect is quite small. He finds, qualitatively, that it is possible to obtain the following states in O^{18}: $E(0+)$, 0 Mev; $E(2+)$, 2.0 Mev; $E(4+)$, 3.5 Mev; $E(0+)$, 3.9 Mev; and $E(2+)$, 4.3 Mev by using $V_c=40$ Mev and a value of the surface particle coupling parameter compatible with the value required for F^{19}.[23] To test this idea, it would be of considerable interest to measure the spin of the known level in O^{18} at 3.93 Mev and to search for a possible level in O^{18} near 4.4 Mev.

The enhanced $E2$ transition probability for the transition between the 7.13-Mev and 1.98-Mev levels in O^{18} and the fact that the alpha-particle width equals or exceeds the average values for allowed alpha transitions in light nuclei might suggest some connection between the 4+ level at 7.13 Mev and the 0+ ground state and 2+ first excited state of O^{18}. Using the $J(J+1)$ rule for level spacings given by the strong-coupling collective model,[25] the 4+ state associated with the ground-state band would lie at an excitation 6.6 Mev. A comparison of the energy positions of 2+ first excited states in even-even nuclei in this region of mass number suggests that O^{18}, Ne^{20}, and Mg^{24} are the most distorted nuclei in the region. Evidence that nuclei of mass 25 and 24 are reasonably well explained on the strong-coupling collective model is surprisingly strong.[26] Similar evidence exists for F^{19}.[27] It is, therefore, of some interest to make a similar comparison for O^{18}.

If the potential energy as a function of distortion is computed for elements in the d shell beyond O^{16} using the Nilsson eigenvalues,[28] prolate distortions are found to be most stable until the region of mass 29. In previous calculations prolate distortions have been found to give agreement with experiment for F^{19},[27] Al^{25}, Mg^{25},[26] and Al^{28},[29] while some evidence for an oblate shape exists for Si^{29}.[30] The observed[31] negative quadrupole moment of O^{17} of -0.026 barn is not necessarily evidence for an oblate shape since one would expect the odd neutron to be in Nilsson's orbit 6 ($d_{\frac{5}{2}}$, $K=\frac{1}{2}$). In this case, for values of the decoupling parameter ≥ 4, the $I=\frac{5}{2}$ level lies below $I=\frac{1}{2}$, and under these conditions the observed quadrupole moment has the opposite sign to that of the intrinsic quadrupole moment.[32] The computed value of the decoupling parameter using Nilsson's wave functions varies from about 2 to 3 and suggests that the condition is very close to being fulfilled.

If a prolate distortion is assumed for O^{18}, the two neutrons outside the closed O^{16} shell would lie in the Nilsson orbit 6 ($d_{\frac{5}{2}}$, $K=\frac{1}{2}$) in the ground state and would have $K=0$. This might account for the levels 0 Mev (0+), 1.98 Mev (2+), and 7.13 Mev (4+). The next higher intrinsic configuration could come from one neutron moving to the next orbit number 7 ($d_{\frac{5}{2}}$, $K=\frac{3}{2}$). In this case two bands could be formed with $K=1$ and $K=2$. If all levels below 4 Mev have been observed, the 4+ state at 3.55 Mev must belong to one of the bands and must have been shifted by rotational particle coupling. However, no reasonable set of parameters has been found to fit such a low excitation for this 4+ level. If both neutrons are promoted to the ($d_{\frac{5}{2}}$, $K=\frac{3}{2}$) orbit, the combination can produce only another $K=0$ band without violating the exclusion principle. This would not mix, to first order, with the ground-state band and, thus, cannot explain the low-lying 4+ level at 3.55 Mev. This evidence rather conclusively argues against the strong-coupling collective model for O^{18}.

Elliott has recently been considering collective motion in the nuclear shell model.[33] He has shown that the orbital wave functions in L-S coupling for a number of nucleons in a degenerate level of an oscillator potential can be classified in representations labelled by a pair of integers $(\lambda\mu)$ and has demonstrated that for nuclei of mass 18, 19, and 20 the wave functions so defined had a greater than 90% overlap with those resulting from standard shell-model calculations. Each representation $(\lambda\mu)$ contains a set of states with different values of the total orbital momentum L (for the low lying levels of O^{18} only singlet states are involved and $L=J$). These values are precisely those obtained

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for a series of rotational bands but cut off at some upper limit. Each band can be assigned a value of K given by

$$K=\min(\lambda\mu),\ \min(\lambda\mu)-2,\ \cdots 1 \text{ or } 0.$$

The values of L (or J in this case) which are permitted for each band are

$$L=K,\ K+1,\ K+2,\ \cdots[K+\max(\lambda\mu)].$$

In the case of O^{18} the three lowest representations $(\lambda\mu)$ are (40), (02), and (21) in increasing order of excitation. This gives rise to three bands in O^{18}; $K=0$ with $J=0$, 2 and 4; $K=0$ with $J=0$, and 2; and $K=1$ with $J=1$ and 2. Although the present status of the calculations is such that the relative spacings between bands and spacings of levels within a band cannot be estimated with any exactitude, the spins of the 3.93-Mev level and higher levels, if measured, would provide a test of the theory.

In conclusion, it is evident that nuclei of mass 18 are of considerable interest at present. It would be useful to obtain more experimental information about levels in O^{18}, and this will probably involve reactions other than $C^{14}(\alpha,\gamma)$.

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APPENDIX. SPIN AND PARITY OF THE 3.55-MEV LEVEL IN O^{18}

It will now be shown that the angular distributions measured at the resonance at 1.14 Mev, corresponding to the level at 7.13 Mev in O^{18}, and listed in Table I, are sufficient to establish the spin and parity of both the 7.13- and the 3.55-Mev levels. Measurements at the 1.79-Mev resonance establish an assignment of 2+ for the first excited state at 1.98 Mev. Table IV lists the theoretical correlations for gamma rays from alpha particle capture by a 0+ target nucleus for various values of J for the capturing state and a spin and parity of 2+ for the final state. Comparing the measured coefficients for the distribution of the 5.15-Mev gamma rays given in Table I, which, corrected for solid angle, are $a_2/a_0=+0.56\pm0.08$ and $a_4/a_0=-0.47\pm0.11$, with those listed in Table IV, one obtains either $J=4+$ for the capturing state or $J=2+$ with an $E2$-$M1$ amplitude ratio ranging from about -1.8 to -2.3. It should be noted that in Table IV where an $M1$-$E2$ mixture is possible there are three terms contributing to the a_2/a_0 coefficient. In the case of a 2+ to 2+ gamma transition, for example, one writes

$$a_2/a_0=(+0.500-1.460x-0.153x^2)/(1+x^2),$$
$$a_4/a_0=-0.490x^2/(1+x^2),$$

where x is the amplitude ratio of $E2$ to $M1$ and can range from $-\infty$ to $+\infty$. The negative sign for x corresponds to the two multipoles having a phase difference of 180° while a positive sign means 0° phase difference.

TABLE IV. Theoretical angular distributions for gamma rays from alpha-particle capture by a 0+ target nucleus into a compound state $J\pi$ and leading to a final 2+ state.

$$W(\theta)=1+(a_2/a_0)P_2(\cos\theta)+(a_4/a_0)P_4(\cos\theta).$$

Spin and parity of capturing state $J\pi$	Radiation	Angular distribution coefficients a_2/a_0	a_4/a_0
0+	$E2$	0	0
1−	$E1$	−0.100	0
2+	$M1$	+0.500	0
2+	$E2$	−0.153	−0.490
2+	$M1$-$E2$[a]	−1.460	0
3−	$E1$	−0.400	0
4+	$E2$	+0.510	+0.368

[a] The complete expressions for the a_2/a_0 and a_4/a_0 coefficients in the case of an $M1$-$E2$ mixture for this example are given in the Appendix. The sign of the coefficient of this term corresponds to a zero phase difference between the $M1$ and $E2$ parts of the mixture using the convention of W. T. Sharp *et al.* (reference 16) but modified by the Huby correction [R. Huby, Proc. Phys. Soc. (London) **A67**, 1103 (1954)].

Turning now to the angular distribution of the 3.58-Mev gamma rays, the coefficients corrected for finite geometry obtained from Table I are $a_2/a_0=+0.45\pm0.06$ and $a_4/a_0=-0.10\pm0.09$. With the capturing state established as either 4+ or 2+, it is possible to place limits on the spin of the 3.55-Mev level. Table V lists the theoretical angular-distribution coefficients for various possible combinations for the capturing state $J=4$ or 2 and the final state $I=0$, 1, 3, or 4. The cases for $I=2$ are given in Table IV. Comparing the measured correlation of the 3.58-Mev gamma rays with theory gives the following possibilities for J and I: 4+ to 4+ with $x=-0.04$ to -0.14, 2+ to 3+ with $x=0.45$ to 1.50, or 2+ to 2+ with $x=+0.02$ to $+0.08$.

TABLE V. Theoretical angular distributions for gamma rays from alpha particle capture by a 0+ target nucleus into a compound state J and leading to a final state I.

$$W(\theta)=1+(a_2/a_0)P_2(\cos\theta)+(a_4/a_0)P_4(\cos\theta).$$

J	I	Radiation	Angular distribution coefficient a_2/a_0	a_4/a_0
4	4	$M1$ or $E1$	+0.500	0
		$E2$	−0.302	+0.601
		$M1$-$E2$[a]	+0.764	0
4	3	$M1$ or $E1$	−0.357	0
		$E2$	−0.051	+0.735
		$M1$-$E2$[a]	−2.143	0
2	4	$E2$	+0.204	−0.014
2	3	$M1$ or $E1$	−0.143	0
		$E2$	−0.408	+0.122
		$M1$-$E2$[a]	+1.565	0
2	1	$M1$ or $E1$	−0.500	0
		$E2$	+0.357	+1.143
		$M1$-$E2$[a]	−2.236	0
2	0	$E2$	+0.714	−1.714

[a] See reference to Table IV.

TABLE VI. Theoretical angular distributions of the type $(\alpha\gamma_1\gamma_2)$ with γ_1 unobserved from alpha-particle capture by a 0+ target nucleus into a compound state J_1 decaying by γ_1 to a state J_2 which in turn decays by γ_2 to a state J_3.

$W(\theta)=1+(a_2/a_0)P_2(\cos\theta)+(a_4/a_0)(\cos\theta)$.

J_1	γ_1	J_2	γ_2	J_3	a_2/a_0	a_4/a_0
4+	$E2$	2+	$E2$	0+	+0.510	−0.367
2+	$M1$	2+	$E2$	0+	+0.357	+1.143
2+	$E2$	2+	$E2$	0+	−0.153	−0.490

Once again in Table V the a_2/a_0 and a_4/a_0 coefficients should be expressed as functions of x when $M1$-$E2$ mixtures are possible.

Hence, from the direct (α,γ) correlations at this resonance one can only conclude that the capturing state is 4+ or 2+ and the excited state at 3.55 Mev in O^{18} is 2+, 3+, or 4+ with only the combinations 4+ to 4+, 2+ to 2+, 2+ to 3+ possible for the 3.58-Mev gamma rays. In each possible case the $M1$-$E2$ mixture in the 3.58-Mev radiation is established. Of the two remaining angular distributions, those of the 1.57- and the 1.98-Mev gamma rays, the former would seem to be more likely to provide further limitations on the spin of the 3.55-Mev level since it is an angular correlation of the form $(\alpha,\gamma_1,\gamma_2)$ with γ_1 unobserved, it arises only from this mode of decay and it proceeds directly from the 3.55-Mev state. In fact, however, the angular distribution of the 1.57-Mev gamma rays is consistent with each of the three possible combinations of spin and parity for the 7.13 and 3.55-Mev levels. This is a simple consequence of the fact that when γ_2 in the correlation $(\alpha,\gamma_1,\gamma_2)$ with γ_1 unobserved can involve an $M1$-$E2$ mixture, as in two of the cases under consideration, the term in the correlation involving the amplitude of this mixture can vary over a wide range of positive and negative values which readily encompass the experimental values of the coefficients given in Table I. In the case where the 7.13, 3.58, and 1.98 levels are assumed to be 4+, 4+, and 2+, respectively, there is no mixture in the second radiation (it is pure $E2$). Since the $M1$-$E2$ mixture in the first radiation is known ($x=-0.04$ to -0.14) from the distribution of the 3.58-Mev radiation discussed above, one can predict what the distribution of the 1.57-Mev radiation should be; namely, $W(\theta)=1+0.434P_2-0.184P_4$. The measured correlation corrected for finite geometry obtained from Table I is $W(\theta)=1+(0.42\pm0.08)P_2-(0.19\pm0.12)P_4$, which is quite satisfactory agreement.

There remains finally then the angular distribution of the 1.98-Mev gamma rays with respect to the incident alpha-particle beam. Reference to Fig. 6 shows that the measured angular correlation is a result of two superposed correlations—the first of the type $(\alpha,\gamma_1,\gamma_2)$ with γ_1 unobserved resulting from the direct feeding of the 1.98-Mev state by the 5.15-Mev radiation, and the second of the type $(\alpha,\gamma_1,\gamma_2,\gamma_3)$ with γ_1 and γ_2 unobserved resulting from the triple cascade of 3.58-, 1.57-, and 1.98-Mev gamma rays. The first correlation can be calculated uniquely for a capturing state of spin and parity of either 4+ or 2+, using for the 2+ case the $M1$-$E2$ mixture required to fit the angular distribution of the 5.15-Mev gamma rays. The theoretical expressions are given in Table VI. If one takes the $M1$-$E2$ amplitude ratio for the first radiation to be $x=-1.8$ to -2.3, which is the value found from the distribution of the 5.15-Mev gamma rays assuming 2+ for the capturing state, one can add the two distributions listed in Table VI for the $2+\rightarrow2+\rightarrow0+$ case to obtain the following distribution for the 1.98-Mev gamma rays arising from the double cascade: $W(\theta)=1-(0.050\pm0.020)P_2-(0.172\pm0.063)P_4$, where the range of values for the coefficients corresponds to the range of amplitude mixtures x. This distribution and the first one listed in Table VI can be separately subtracted from the experimentally observed distribution of the 1.98-Mev radiation which, corrected for finite geometry (see Table I), is $W(\theta)=1+(0.485\pm0.081)P_2-(0.358\pm0.119)P_4$. In this subtraction one must take into account the measured branching ratio, which shows that only 44% of the 1.98-Mev gamma-ray transitions are due to direct feeding of the 1.98-Mev level by 5.15-Mev gamma rays; and the final results are the angular distribution of the 1.98-Mev gamma rays from the triple cascade alone for the two possible spin assignments for the capturing state. These are $W(\theta)=1+(0.47\pm0.14)P_2-(0.35\pm0.21)P_4$ assuming 4+ for the capturing state, and $W(\theta)=1+(0.90\pm0.15)P_2-(0.50\pm0.21)P_4$ assuming 2+ for the capturing state.

It is now necessary to compare these distributions with theory for correlations of the type $A(\alpha,\gamma_1,\gamma_2,\gamma_3)$, where the target nucleus A has spin and parity 0+ and the intensity of γ_3 is measured as a function of angle with respect to the incident alpha-particle beam; γ_1 and γ_2 are unobserved. This sequence can be written $J_1(L_1L_1')J_2(L_2L_2')J_3(L_3L_3')J_4$. The incoming orbital angular momentum of the alpha particle required to form a state of spin J_1 in the compound nucleus will be equal to J_1 and, in the case with which we are dealing, $J_3=2$, $J_4=0$, and $L_3=L_3'=2$. Apart from trivial

TABLE VII. Theoretical angular distributions of the type $(\alpha\gamma_1\gamma_2\gamma_3)$ with γ_1 and γ_2 unobserved from alpha-particle capture by a 0+ target nucleus into a compound state J_1 decaying by γ_1 to a state J_2 which decays by γ_2 to a state J_3 which in turn decays by γ_3 to a state J_4. $W(\theta)=a_0+a_2P_2(\cos\theta)+a_4P_4(\cos\theta)$.

J_1	γ_1	J_2	γ_2	J_3	γ_3	J_4	a_0	a_2	a_4
4	$M1$	4	$E2$	2	$E2$	0	1	+0.434	−0.184
4	$E2$	4	$E2$	2	$E2$	0	1	+0.292	+0.055
2	$M1$	2	$M1$	2	$E2$	0	1	+0.178	−0.762
2	$E2$	2	$M1$	2	$E2$	0	1	−0.077	+0.327
2	$M1$	2	$E2$	2	$E2$	0	1	−0.077	+0.327
2	$E2$	2	$E2$	2	$E2$	0	1	+0.033	−0.140
2	$M1$	3	$M1$	2	$E2$	0	1	+0.490	−0.299
2	$E2$	3	$M1$	2	$E2$	0	1	+0.122	+0.449
2	$M1$	3	$E2$	2	$E2$	0	1	+0.122	+0.449
2	$E2$	3	$E2$	2	$E2$	0	1	+0.031	−0.673

factors involving powers of -1, the theoretical expression[16] for one term of such a correlation is

$$W(\theta)=\sum_k Z(J_1J_1J_1J_1,0k)W(J_1J_2J_1J_2,L_1k) \times W(J_22J_22,L_2k)Z_1(2222,0k)P_k(\cos\theta).$$

The number of such terms required depends on the possible multipole mixtures involved in the gamma-ray transitions between J_1 and J_2 and J_2 and J_3. If, for example, both of these involve $M1$-$E2$ mixtures, then there will be four terms in the correlation as in the case J_1, J_2, J_3, J_4=2+, 2+, 2+, 0+, where the terms are

(a) 2+($M1$)2+($M1$)2+($E2$)0+,

(b) 2+($E2$)2+($M1$)2+($E2$)0+,

(c) 2+($M1$)2+($E2$)2+($E2$)0+,

(d) 2+($E2$)2+($E2$)2+($E2$)0+.

It is to be noted that no terms involving the amplitude $M1$-$E2$ mixtures for the same radiation occur and hence only the intensity ratios of such mixtures are required. If x^2 and y^2 are the $E2$-$M1$ intensity ratios for the first and second radiations, the above four terms would be multiplied by 1, x^2, y^2, and x^2y^2, respectively.

Theoretical distributions of this type have been calculated for the three possible combinations (4+, 4+, 2+, 0+), (2+, 2+, 2+, 0+), and (2+, 3+, 2+, 0+) and are listed in Table VII. The $E2$-$M1$ intensity mixture for the first radiation is known in each case from comparison between the direct correlation of the 3.58-Mev radiation and theory as described previously. It is essentially zero for the first two cases and ranges from 0.2 to 2.25 for the third case. Thus the corrected measured angular correlation [i.e., corrected as described above for the $(\alpha,\gamma_1,\gamma_2)$ contribution] must be compared with the first line of Table VII if the capturing state is 4+. Since, in this case, the experimental values are $a_2/a_0=+0.47\pm0.14$ and $a_4/a_0=-0.35\pm0.21$, agreement is obtained for the combination (4+, 4+, 2+, 0+) for the 7.13-, 3.55-, 1.98-, and 0-Mev levels, respectively. The comparison between theory and experiment for the second and third combinations above, where the capturing state is 2+, is illustrated in Fig. 7. Here the theoretical a_2/a_0 and a_4/a_0 coefficients are plotted as a function of y^2, the intensity ratio of $E2$ to $M1$ radiation in the second transition (between the 3.55- and 1.98-Mev levels), assuming $x^2=0$ for the (2+, 2+, 2+, 0+) case and assuming $x^2=0.2$ and 2.25 for the (2+, 3+, 2+, 0+) case, where x^2 is the $E2$-$M1$ intensity mixture in the first radiation. The corrected experimental values of $a_2/a_0=+0.90\pm0.15$ and $a_4/a_0=-0.50\pm0.21$ are also shown. It is clear that in neither case is agreement obtained, and hence the spin and parity of both the 7.13-Mev and 3.55-Mev levels in O^{18} are 4+.

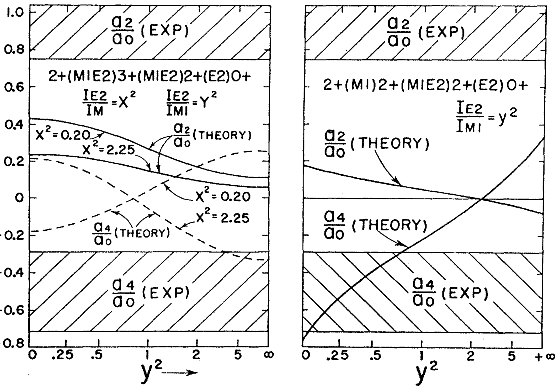

FIG. 7. Comparison between experiment and theory for the angular distribution of that fraction of the intensity of 1.98-Mev gamma rays arising only from the triple cascade at the 1.14-Mev resonance. The two cases considered are those in which the spins and parities of the 7.13, 3.55, 1.98, and 0-Mev levels are 2+, 3+, 2+, and 0+; and 2+, 2+, 2+, and 0+, respectively. In both cases the distribution is assumed to be

$$W(\theta)=1+(a_2/a_0)P_2(\cos\theta)+(a_4/a_0)P_4(\cos\theta),$$

and the coefficients a_2/a_0 and a_4/a_0 are plotted as a function of the $E2$ to $M1$ intensity mixture y^2 of the second radiation. For the 2+, 3+, 2+, 0+ case the theoretical curves are shown for the upper and lower limits of the $E2$ to $M1$ intensity mixture x^2 of the first radiation. The experimental coefficients are shown as shaded horizontal bands.