Angular-Correlation Studies of the Reactions $O^{16}(He^3,\alpha\gamma)O^{15}$, $C^{12}(He^3,p\gamma)N^{14}$, and $C^{12}(d,p\gamma)C^{13}$

S. Gorodetzky, R. M. Freeman, A. Gallmann, and F. Haas
Institut de Recherches Nucléaires, Strasbourg, France
(Received 16 March 1966)

Mixing ratios of some gamma-ray transitions in O^{15}, N^{14}, and C^{13} have been studied by particle-gamma angular-correlation measurements for the reactions $O^{16}(He^3,\alpha\gamma)O^{15}$, $C^{12}(He^3,p\gamma)N^{14}$, and $C^{12}(d,p\gamma)C^{13}$. The outgoing particles were detected close to 180° in an annular counter. For the He^3 beam energies available it was possible to study all the bound states of N^{14}, but only the 5.18–5.24-MeV doublet (unresolved) and the 6.16-MeV level of O^{15} could be studied in detail. An attempt was also made to obtain the mixing ratio of the ground-state transition from the 3.85-MeV level of C^{13}. Spin assignments were verified wherever possible and the spin of the 5 24-MeV level of O^{15} has been established as $\frac{5}{2}$ Gamma-ray branching ratios were determined for the levels of N^{14} and were generally in agreement with previous work. Strong evidence was found for a weak transition between the 5.10-MeV and 3.95-MeV states of N^{14}, but the previously reported transition between the 7.03 and 3.95-MeV states was not observed. Correlations for the $C^{12}(He^3,p\gamma)N^{14}$ reaction were measured at four different energies, since they can vary with energy. It was found from the correlations that the N^{14} levels were strongly populated in the $m=0$ substate. This has been interpreted as due to a direct interaction, possibly heavy-particle stripping.

I. INTRODUCTION

THE method described by Litherland and Ferguson[1] (method II) has been used to verify the spins of levels and obtain mixing ratios of the gamma-ray transitions in the nuclei O^{15}, N^{14}, and C^{13}. The levels were excited by the reactions $O^{16}(He^3,\alpha\gamma)O^{15}$, $C^{12}(He^3,p\gamma)N^{14}$, and $C^{12}(d,p\gamma)C^{13}$. As in the present experiments where the outgoing particles are detected close to 180° in an annular detector, the correlations between the particles and the decay gamma rays depend on a few parameters involving the alignment of the excited nuclei along the beam direction and the mixing ratios of the gamma-ray transitions. This is particularly simple in the case of the $O^{16}(He^3,\alpha\gamma)O^{15}$ reaction, where the sum of the spins of the target nucleus, and of the ingoing and outgoing particles, is $\frac{1}{2}$. In these circumstances only the magnetic substates $\frac{1}{2}$ and $-\frac{1}{2}$ of the O^{15} levels are populated to a first approximation. The positive and negative m states being equally populated, the only parameter to enter the expressions for the correlations will be the mixing ratios of the decay gamma rays. The expressions for the correlations are more complicated for the reaction $C^{12}(He^3,p\gamma)N^{14}$ since the $m=1$, 0, and -1 substates are populated and an extra parameter to describe the ratio between the populations is therefore required. The angular correlations and decay schemes for the levels of N^{14} were sufficiently complex that the additional parameter presented no problems. Unlike the correlations for the $O^{16}(He^3,\alpha\gamma)O^{15}$ reaction, the correlations for the $C^{12}(He^3,p\gamma)N^{14}$ reaction can change with beam energy, and were therefore measured for several energies.

II. EXPERIMENTAL PROCEDURE

A number of experiments have been described using several techniques to measure particle-gamma correlations where the particles are detected close to 0° or 180°. The method used in the present experiments is similar to that described by Poletti and Warburton,[2] where the particles are detected near 180° in an annular detector.

The He^3 beam was first collimated to about 3 mm diam and entered the target chamber through the central hole of the annular detector. The beam left the chamber by a tube 1.5 cm in diameter and was eventually stopped on an aluminum plate at 2.5-m distance. The target chamber was 12.0 cm in diameter with brass walls 3.0-mm thick.

Since these experiments a new chamber, similar to that used by the Brookhaven group,[3] has been put into operation. With this new chamber, measurement of the gamma-ray intensity can be made at 0° to the incident-beam direction.

The particle detector was a silicon semiconductor counter (1000 Ω cm, n type) which had a central hole 6 mm in diameter. It was normally fixed at 4 cm from the target where the shielding on the front face of the detector limited the angles of the detected particles to the range from 174° to 169°. The effect on the angular correlation of detecting the particles at angles less than 180° will be considered in Sec. III. The intrinsic resolution of the counters was measured to be about 50 keV, though under experimental conditions the performance of the counters deteriorated and resolutions were commonly of the order of 100 keV. A spectrum taken during one of the $C^{12}(He^3,p\gamma)N^{14}$ experiments is shown in Fig. 1. In this spectrum proton groups to all the bound states of N^{14} are indicated except to the ground and first excited states which were not stopped in the depletion layer. The applied bias of 50 V was sufficient to stop protons of about 4 MeV. Three other strong

[1] A. E. Litherland and A. J. Ferguson, Can. J. Phys. **39**, 788 (1961).

[2] A. R. Poletti and E. K. Warburton, Phys. Rev. **137**, B595 (1965).

[3] D. E. Alburger and E. K. Warburton (private communication).

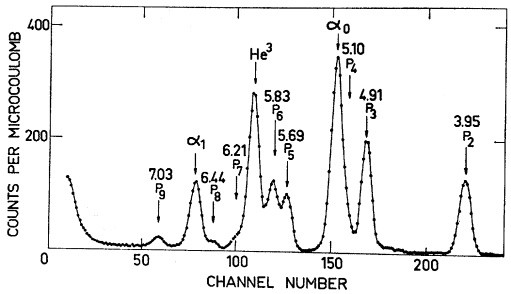

FIG. 1. Particle spectrum from the annular counter for the reaction $C^{12}+He^3$. The spectrum obtained at a bombarding energy of 4.90 MeV was recorded on a 400-channel analyzer. Peaks due to the elastically scattered He^3 and to groups from the $C^{12}(He^3,p\gamma)N^{14}$ and $C^{12}(He^3,\alpha\gamma)C^{11}$ reactions are indicated with the excitation energy of the final nucleus given in MeV. Proton groups to all the bound states of N^{14} are marked except the ground and first excited states which were not stopped in the barrier region.

peaks observed in the spectrum correspond to the elastically scattered He^3 and alpha groups to the ground and first excited state of C^{11} from the reaction $C^{12}(He^3,\alpha\gamma)C^{11}$.

The gamma-ray detector was a 5-in.×6-in. NaI(Tl) crystal which could be rotated in a horizontal plane about the center of the target chamber. For all the experiments the front face of the crystal was 28.5 cm from the target. Because of the exit tube from the chamber previously mentioned, the crystal could not be rotated to angles less than 20°. The centering was checked with a cobalt source in the target position. The count rate in the crystal was found to be constant to within 1% for all angles from 90° to 30°, but a 7% attenuation of the gamma-ray intensity was found for an angle of 20° due to the exit tube and flanges. Corrections for this attenuation, allowing for its energy dependence, were made to all the angular correlations.

The particle-gamma coincidences were recorded on a two-dimensional 20 000-channel analyzer in order that all the possible angular correlations could be measured simultaneously. A memory configuration of 200×100 channels, 200 channels for the gamma-ray spectrum and 100 channels for the particle spectrum, was always used. The analyzer was gated externally by a fast-slow coincidence unit, having a time resolution 2τ of approximately 60 nsec. The angular correlations were monitored by one of the peaks in the particle spectrum. The total-coincidence and random-coincidence rates were also recorded. Random-coincidence rates were usually between 5 and 10% of the total-coincidence rate.

III. ANALYSIS OF THE DATA

For reasons of speed, the spectra from the two-dimensional analyzer were first recorded on magnetic tape. They were afterwards punched on paper tape ready for analysis by a computer. The computer, IBM 1620 II, sorted the spectra into subspectra corresponding to windows on both the particle and gamma-ray energies. These windows were corrected for any gain shifts occurring during the experiment, and for the Doppler shifts. The angular correlations were then deduced from subspectra corresponding to windows on the particle energies.

The purpose of the windows on the gamma-ray energies was to assess the number of random coincidences. Though in principle it is possible to calculate the number of randoms for any subspectrum from the total random-coincidence rate, it was simpler to place a window on the gamma-ray energies and determine the number of counts in one of the peaks not in coincidence with gamma rays. In only a few cases was the correction for the number of randoms important.

The errors given for the experimental points of the correlations are those expected statistically, i.e., in the simplest cases the square root of the number of counts. For the correlations where the statistical error was very small the scatter of experimental points was improbably large due to some other form of error. The errors for these correlations, and for any correlation where other forms of error have been suspected, have been increased by as much as a factor 2. The angular correlations were fitted by a minimum χ^2 calculation to an expression of the form

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

where the expansion was terminated at a_2, a_4, and a_6 successively. For only one level studied were the terms in a_6 taken into consideration. The errors on the coefficients are quoted to one standard deviation and were calculated by the method given by Rose.[4] The coefficients are always given in this article, except where otherwise indicated, without correcting for the finite solid angle subtended at the target by the NaI crystal. Where the attenuation factors have been required they have been taken from the tables of Rutledge,[5] i.e., 0.97 for a_2 and 0.91 for a_4.

The coincidence gamma-ray spectra which are shown in this article were obtained by adding together the results for the different angles. Simple addition of the spectra, however, resulted in poor resolution for the gamma rays due to Doppler shifts and electronic gain shifts, especially for the high-energy gamma rays. Because there were a large number of gamma-ray calibration points in the two-dimensional spectra, the shifts could be measured quite accurately and were corrected for in the same computer program which added the spectra together. In this way good statistics were obtained without sacrificing resolution. Resolutions of 4% and better (full width at half-maximum) were achieved for the 7.03-MeV gamma ray of N^{14}, the highest energy gamma ray studied in this work.

[4] M. E. Rose, Phys. Rev. 91, 610 (1953).
[5] A. R. Rutledge, Atomic Energy of Canada Limited, Report No. 1450, 1964 (unpublished).

Where a state was observed to decay to more than one level, the gamma-ray branching ratios were verified. The relative intensity of the gamma ray was determined from curves for the photofractions (the ratio of the photopeak to total spectrum) and the total efficiency. The total efficiency was calculated for the appropriate geometry with a computer program. Values for the photofractions were extrapolated from the calculated values of Miller, Reynolds, and Snow,[6] and results were also available from the report by Young, Heaton, Phillips, Forsyth, and Marion[7] for a 5-in.×5-in. crystal, the photofractions of which should not differ greatly from those of the crystal used in this work. The latter results were finally used, as they covered completely the energy range required and the values were in better accord with the photofractions observed experimentally. Good agreement was obtained when the intensity of a gamma-ray cascade was determined from more than one of the gamma rays, even where there was a considerable difference between the gamma-ray energies. This demonstrated that the photofractions used had the correct energy dependence. The angular correlations, where known, were taken into account in determining the gamma-ray intensities. The intensities were also corrected for the difference in absorption in the walls of the target chamber.

The experimental results have been exploited by the same methods employed by other authors for similar experiments,[2] i.e., by supposing a certain set of spin values and determining the χ^2 for the best fit possible to the experimental correlations for values of the mixing ratio from $-\infty$ to $+\infty$. For this purpose a computer program was used which was capable of treating up to two gamma-ray correlations from the decay of a level, with or without a population parameter, and with the possibility of varying the mixing ratio of both gamma rays. From these analyses, results true to a high degree of statistical probability have been determined. Where a result is given to a high degree of statistical probability, as in the cases of firm spin assignments, a statistical probability of 99.9% or better is implied. Graphical solutions have generally been presented in this article since all four results for the $C^{12}(He^3,p\gamma)N^{14}$ reaction can be treated together by this means.

Graphical solutions are simple for the $O^{16}(He^3,\alpha\gamma)O^{15}$ reaction since the correlations depend to the first approximation only on the mixing ratios. On the other hand, a population parameter also enters the expression for the correlations for the reaction $C^{12}(He^3,p\gamma)N^{14}$. The population parameter can sometimes be eliminated by the following method. Consider a level with spin a, which decays to two other levels with spin b and c. Then the correlation for the transition $a\rightarrow b$ will be described by[2]

$$a_k=\rho_k(a)F_k(ab)Q_k\,, \tag{1}$$

where a_k is the coefficient of the Legendre polynomial of order k, $\rho_k(a)$ is a statistical tensor which contains the population parameters, $F_k(ab)$ contains the mixing ratio for the transition, and Q_k is the attenuation factor arising from the solid angle subtended by the gamma-ray counter. Similarly the correlation for the transition $a\rightarrow c$ will be described by

$$a_k'=\rho_k(a)F_k(ac)Q_k\,. \tag{2}$$

If the ratio between the coefficients of the same order Legendre polynomial is taken, then

$$a_k/a_k'=F_k(ab)/F_k(ac)\,, \tag{3}$$

which depends only on the mixing ratios of the two transitions. If spin c is zero then $F_k(ac)$ is simply a number since the transition is pure, and only the mixing ratio of the transition $a\rightarrow b$ appears as a parameter in formula (3).

In the formulas given above no assumption has been made that the particles were detected at 180°, or that only a few magnetic substates were populated. The assumption may be made in order to calculate $\rho_k(a)$, but the statistical tensor disappears in formula (3). This does not mean that the use of an annular detector was unimportant where the correlations were analyzed using formula (3). The formulas do assume that there is axial symmetry about the beam direction, and this is conveniently achieved by detecting the outgoing particles in an annular detector close to 180°. Moreover, if the magnetic substates are limited to a few m values, as happens when the particles are detected near 180°, the angular correlations are generally stronger than they would otherwise be.

Similar expressions to those of formulas (1) and (2) can be given for the correlation of a transition which is not the first member of a cascade. Supposing, for example, that the state with spin c in the example given previously decays to a state with spin d, then the angular correlation of the transition $c\rightarrow d$ would be described by

$$a_k''=\rho_k(a)U_k(ac)F_k(cd)Q_k\,, \tag{4}$$

where $U_k(ac)$ contains the mixing ratio for the transition $a\rightarrow c$. It will be noted that the same term $\rho_k(a)$ is common to all the correlations associated with the level with spin a. It follows that the coefficients for a particular order Legendre polynomial for the angular correlations of a given level should always be in constant ratio. This fact has been used to check consistency of the experimental results.

The coefficients given in the above formulas have been calculated from the tables given by Poletti and Warburton.[2] They have also been verified using the

[6] W. F. Miller, J. Reynolds, and W. J. Snow, Argonne National Laboratory Report No. 5902, 1958 (unpublished).

[7] F. C. Young, H. T. Heaton, G. W. Phillips, P. D. Forsyth, and J. B. Marion, University of Maryland Technical Report No. 490 (unpublished).

tables of Sharp, Kennedy, Sears, and Hoyle.[8] For the sign of the mixing ratio, the sign convention of Litherland and Ferguson[1] has been used.

It has not always been possible to analyze the results using formula (3), as this requires that accurate angular correlations should be found for two transitions from a level, where one transition should normally be a pure multipole. The method is applicable to several states in N^{14} where there are important transitions to both the 1^+ ground state and the 0^+ first excited state. For other levels the assumption has to be made that the particles are detected close to 180° and corrections for the finite size effect of the particle counter have to be considered. These corrections cannot be calculated without a detailed knowledge of the reaction mechanism. Instead, the effect has been considered by supposing that the magnetic substates are not strictly limited to the few m values possible if the particles were detected exactly at 180°, but that 10% of the population is in the next magnetic substate. For example, for the $C^{12}(He^3,p\gamma)N^{14}$ reaction, the value of $P(2)$, the population of the magnetic substate with $m=2$ would be 0.05 and for the $O^{16}(He^3,\alpha\gamma)O^{15}$ reaction $P(\frac{3}{2})$ would be 0.05. This is quite similar to the convention used by Poletti and Warburton.[2] There was some evidence in the experimental correlations themselves for the magnitude of the finite size effect. For some levels of N^{14} it was possible to say that the value of $P(2)$ was small, and the assumption that $P(2)=0.05$ did not seriously underestimate the finite-size effect. From the results of the 7.03-MeV level, however, there was good evidence that the value of $P(2)$ was less than 0.05.

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

Thin films of Al_2O_3 about 60 $\mu g/cm^2$ thick were employed as oxygen targets. At the beam energy at which the correlations were measured, 5.92 MeV, reactions in the aluminum were not troublesome. The main competing reaction was $O^{16}(He^3,p\gamma)F^{18}$. A large number of gamma rays were seen in coincidence with protons to the levels of F^{18}, to several hundred keV above the $N^{14}+\alpha$ threshold. The gamma rays were not intense enough and the results too complex to obtain any correlations for this reaction. The particle spectrum was very complicated, containing many unresolved particle groups. The gamma-ray transitions in O^{15}, however, were so large in energy that there was no difficulty in separating them from the gamma rays of the $O^{16}(He^3,p\gamma)F^{18}$ reaction. The $C^{12}(He^3,p\gamma)N^{14}$ reaction resulting from the deposit of carbon which built up on the targets was more serious, as the proton groups to states of N^{14} were in coincidence with 6–7-MeV gamma rays.

The levels of O^{15} studied in the present work are shown in Fig. 2, where probable values of the spins and parities of the levels and the gamma-ray transitions observed are also indicated. Correlations were measured for five angles between 20° and 90°, each angle being repeated at least once. In effect only two correlations were obtained because of the limited beam energy available, one for the first two excited states which were unresolved in this experiment and the other for the 6.16-MeV third excited state. Other states were too feebly excited to be studied, though it was noted that either the 6.85- or 6.79-MeV level decayed to the first or second excited state. From recent work[9] on the gamma-ray transitions of O^{15} it is evident that this was the 6.85-MeV level decaying to the 5.24-MeV level. The 6.79–6.85-MeV doublet has recently been studied[10] at the University Laval using the same methods described here but at a He^3 bombarding energy of 9 MeV.

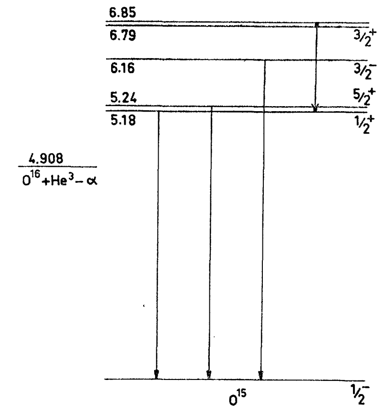

FIG. 2. Level diagram of O^{15} with excitation energies given in MeV, showing gamma rays observed in the present experiments. The spins and parities indicated have been determined experimentally either in this nucleus or the mirror nucleus N^{15}.

The 5.18–5.24-MeV Levels

The angular correlation for the unresolved doublet is shown in Fig. 3(a). The values of a_2 and a_4 determined from the correlations are $+(0.38\pm0.05)$ and $-(0.42\pm0.07)$, respectively. The presence of a large a_4 term demands that the spin of one member of the doublet should be $\frac{5}{2}$ or greater, presumably the 5.24-MeV level. The 5.18-MeV level is believed to have spin $\frac{1}{2}$, though partially on theoretical grounds; the experimental evidence is not entirely conclusive, though the work of Hinds and Middleton[11] on the $O^{16}(He^3,\alpha)O^{15}$ reaction strongly suggests that the state is $\frac{1}{2}^+$. The isotropic correlation found by Povh and Hebbard[12] in gamma-gamma coincidence experiments is consistent with spin

[8] W. T. Sharp, J. M. Kennedy, B. J. Sears, and M. G. Hoyle, Atomic Energy of Canada Limited, Report No. 97, 1954 (unpublished).

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

[10] A. Gallmann, F. Haas, and N. Balaux (private communication).

[11] S. Hinds and R. Middleton, Proc. Phys. Soc. (London) **74**, 775 (1959).

[12] B. Povh and D. F. Hebbard, Phys. Rev. **115**, 608 (1959).

$\frac{1}{2}$ for the 5.18-MeV level, but does not rule out the possibility of spin $\frac{3}{2}$. Attempts were made to fit the experimental correlation assuming spins $\frac{5}{2}$, $\frac{7}{2}$, or $\frac{9}{2}$ for the 5.24-MeV level and $\frac{1}{2}$ or $\frac{3}{2}$ for the 5.18-MeV level. With the intensity of the two gamma rays as parameters and varying the mixing ratios of both transitions, fits were only possible for a spin assignment of $\frac{5}{2}$ for the 5.24-MeV level, though $\frac{1}{2}$ and $\frac{3}{2}$ were possible for the 5.18-MeV level. Curves for the minimum values of χ^2 in the case where the 5.18-MeV level was assumed to have spin $\frac{1}{2}$ are shown in Fig. 4. For spin $\frac{3}{2}$ a new variable is introduced, the mixing ratio of the 5.18-MeV transition, but even with this added complexity spin possibilities of $\frac{7}{2}$ and $\frac{9}{2}$ for the 5.24-MeV level could be eliminated with a high degree of certainty. The 5.24-MeV level can therefore be assigned spin $\frac{5}{2}$.

Assuming, as seems very likely, that the spin of the 5.18-MeV levels is $\frac{1}{2}$, two values are found for the mixing ratio of the 5.24-MeV transition, $+(0.035_{-0.04}^{+0.11})$ and $+(2.5_{-0.6}^{+0.3})$, where the sign is correct for an $M2$-$E3$ mixture. The errors take into account the effect of the finite size of the particle counter, which has been calculated according to the convention described in Sec. III, namely, that $P(\frac{3}{2})=0.05$, and is shown by the dashed line in Fig. 4. In general the values for the mixing ratio are not greatly changed if the 5.18-MeV level is assumed to have spin $\frac{3}{2}$. The relative intensities of the unresolved alpha groups can also be deduced from the results. This value depends sensitively on the finite-size effect, but the 5.24-MeV level was probably more than three times as intensely excited as the 5.18-MeV level.

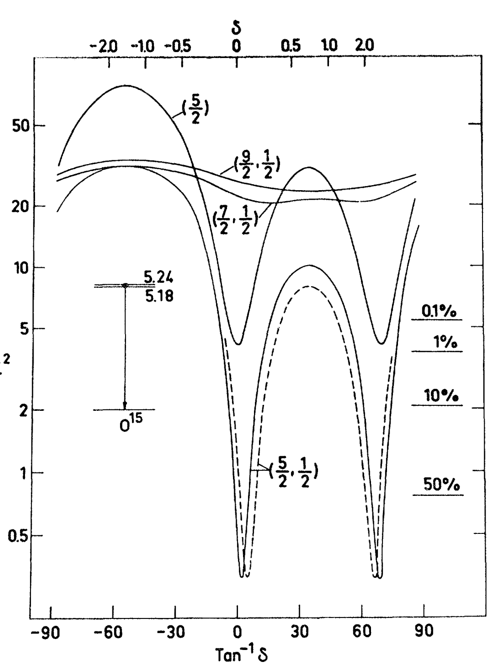

FIG. 4. Minimum χ^2 fits to the correlation for the 5.18–5.24-MeV doublet of O^{15} plotted against the mixing ratio of the 5.24-MeV transition supposing that the 5.18-MeV level has spin $\frac{1}{2}$. Curves are shown assuming spins $\frac{5}{2}$, $\frac{7}{2}$, and $\frac{9}{2}$ for the 5.24-MeV level and also for the case where the correlation is due to a single level with spin $\frac{5}{2}$. The dashed line was calculated for $P(\frac{3}{2})=0.05$ to show the effect of the finite size of the particle counter. The percentages are the statistical probabilities that for the true value of the mixing ratio the value of χ^2 lies above the indicated values.

The 6.16-MeV Level

The correlation for the ground-state transition from the 6.16-MeV level is shown in Fig. 3(b). The analysis of the correlations up to Legendre polynomials of order 4 gave results for a_2 and a_4 of $-(0.14\pm0.07)$ and $+(0.02\pm0.10)$, respectively. No fits were obtained to the experimental results supposing spins $\frac{5}{2}$ and $\frac{7}{2}$ for the 6.16-MeV level. Since the value of a_2 was small and only two standard deviations from zero, the possibility that the state has spin $\frac{1}{2}$ cannot be eliminated with certainty from these results alone. The best fit was obtained supposing the spin to be $\frac{3}{2}$.

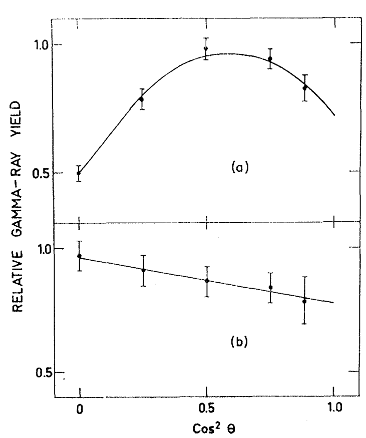

FIG. 3. Particle-gamma angular correlations for the reaction $O^{16}(He^3,\alpha\gamma)O^{15}$. (a) Correlation between alphas to the first two excited states and the ground-state transitions. Line shows the best fit for terms up to $P_4(\cos\theta)$. (b) Correlation between alphas to the 6.16-MeV excited state and the ground-state transition. Line shows the best fit for terms up to $P_2(\cos\theta)$.

For spin $\frac{3}{2}$ the possible values of the mixing ratio can be found from Fig. 5, where δ has been plotted against a_2 for a spin $\frac{3}{2}\rightarrow\frac{1}{2}$ transition. The sign of δ is correct for an $M1$-$E2$ mixture. As before, the dashed line represents the finite-size effect of the particle counter which has been taken into account in assessing the errors on the mixing ratios. The horizontal lines in Fig. 5 show the experimental value for a_2 with errors. Two regions for the mixing ratio are possible, $-(0.19_{-0.07}^{+0.04})$ and $+(2.9_{-0.5}^{+1.1})$. Except for the difference in sign convention these results are in agreement with the two values $+(0.12\pm0.03)$ and $-(2.3\pm0.2)$ found by Povh and Hebbard.[12] As the 6.16-MeV level transition is to the ground state from a level with spin less than 2, a theorem by Van Rinsvelt and Smith[13] is applicable, which shows that no experi-

[13] H. Van Rinsvelt and P. B. Smith, Physica 30, 59 (1964).

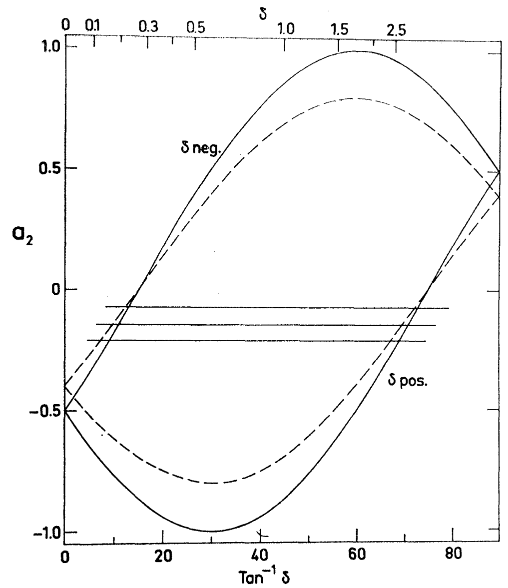

FIG. 5. Calculated values of a_2 for the correlation of a spin $\frac{3}{2}\rightarrow\frac{1}{2}$ transition plotted against the mixing ratio. The experimental value and errors for the correlation of the ground-state transition from the 6.16-MeV level of O^{15} are shown by the horizontal lines. The finite-size effect of the particle counter, considered by supposing $P(\frac{3}{2})=0.05$, is shown by the dashed line.

ment involving only angular correlations and distributions can be devised to resolve the ambiguity of the mixing ratio. The nonzero value of the mixing ratio is strong, though not certain, evidence that the 6.16-MeV transition is an $M1$-$E2$ mixture, and that the spin of the state is negative like the ground state. Recently, the mixing ratio has been measured very accurately[14] as $-(0.17\pm0.01)$ or $+(2.7\pm0.1)$, in good agreement with the present results.

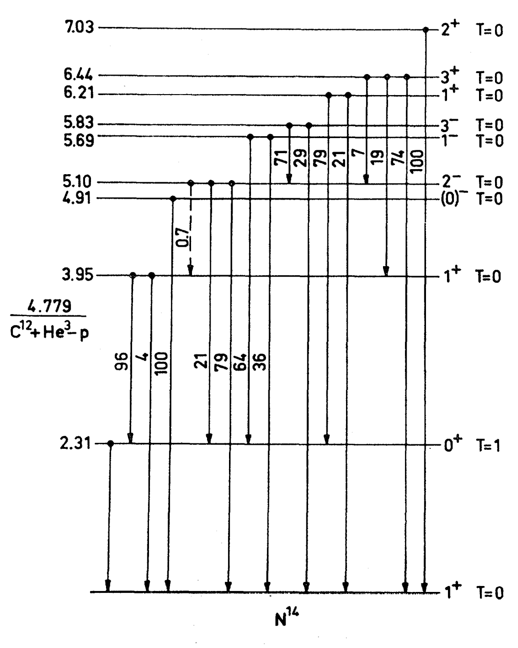

FIG. 6. Levels of N^{14} studied in this work. All gamma-ray transitions which were observed are indicated and the branching ratios are those measured in the present experiments.

V. THE $C^{12}(He^3,p\gamma)N^{14}$ REACTION

Unlike the $O^{16}(He^3,\alpha\gamma)O^{15}$ reaction, the angular correlations for this reaction depend on population parameters which can change with the beam energy. For this reason angular correlations were measured at four different beam energies, 4.62, 4.90, 5.11, and 5.46 MeV. The cross sections for the particle groups of the reaction show some resonant structure and change considerably in the range of energies studied.[15] It was thought therefore that there would be large changes between the correlations at different bombarding energies. It was found, however, that the correlations were generally very similar. Apparently there is an appreciable amount of direct interaction present which favors the population of the $m=0$ substate. In no case was the population parameter $P(0)/P(1)$ found to be less than 1.

The levels of N^{14} studied in the present work are shown in Fig. 6. The spins and parities are well established experimentally except for the spin of the 4.91-

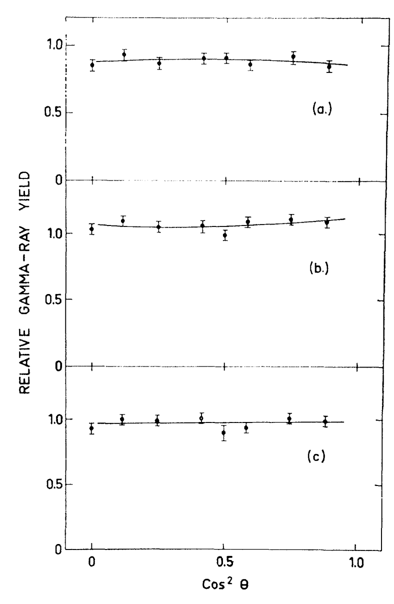

FIG. 7. Correlations for the reactions $C^{12}(He^3,p\gamma)N^{14}$ and $C^{12}(He^3,\alpha\gamma)C^{11}$ which were expected to be isotropic. The beam energy was 4.62 MeV for all three correlations. The lines are for the best-fit coefficients given in Table I. (a) Correlation of the 2.00-MeV gamma ray in coincidence with alphas to the first excited state of C^{11}. (b) Correlation of the 2.31-MeV gamma ray in coincidence with protons to the second excited state of N^{14}. (c) Correlation of the 4.91-MeV gamma ray in coincidence with protons to the third excited state of N^{14}.

[14] J. S. Lopes, O. Häusser, H. J. Rose, A. R. Poletti, and M. F. Thomas, Nucl. Phys. **76**, 223 (1966).

[15] Hsin-Min Kuan, T. W. Bonner, and J. R. Risser, Nucl. Phys. **51**, 481 (1964).

MeV level. Spins between 0 and 4 were considered for all the excited states and in most cases it was possible to confirm the spin assignments from the present results supposing one mixing ratio for each gamma-ray transition. Two notable exceptions were the 4.91- and 5.10-MeV levels. All experimental data for the 4.91-MeV level pointed to spin 0, but spins 1 and 2 could not be eliminated. In the case of the 5.10-MeV level a second mixing ratio had to be introduced into the correlation of the ground-state transition before fits were obtained to the experimental results. Cases where the spin of the level could not be confirmed by the present results will be mentioned.

There was no evidence for any other bound states of N^{14} other than that shown in Fig. 6. Other weak groups seen in the coincidence spectra were identified by their gamma rays as coming from oxygen impurity in the target. Donovan, Mollenauer, and Warburton[16] found no other states in N^{14} until the unbound level at 7.97 Mev. The gamma-ray transitions which were seen in the present experiments and the branching ratios which were measured are shown in Fig. 6. Broadly the results are in agreement with previous work though there are some minor discrepancies.

Since N^{14} is a self-conjugate nucleus, the strengths of the $E1$ and magnetic transitions between states of the same isotopic spin are expected to be weak.[17] There are two consequences of this selection rule which are important. Firstly the mixing ratios are often abnormally large, and secondly transitions to the 0^+, $T=1$ first excited state are relatively strong. The transitions to the first excited state are very useful for analyzing the results because they have a pure multipolarity.

The thin self-supporting carbon targets were about 40 μg/cm^2 thick initially, but increased by as much as 50% during an experiment due to carbon buildup. Correlations were measured for eight angles between 20° and 90°. Each angle was recorded only once as there were several isotropic correlations in the two-dimensional spectra serving as internal checks on the results. A selection of the angular correlations is shown in Figs. 7, 8, 9, and 10, where the results are arranged according to the spin of the level studied, i.e., correlations for all the levels with spin 1 are shown in Fig. 8, etc. The coefficients a_2 and a_4 for the complete set of correlations are listed in Table I. For only one gamma-ray transition, the 5.83-MeV to ground state, were the a_6 terms also significant. For the states with spin 1 the analysis to only a_2 is given but for the correlations which are expected to be isotropic both a_2 and a_4 are listed as an indication of the accuracy of the coefficients.

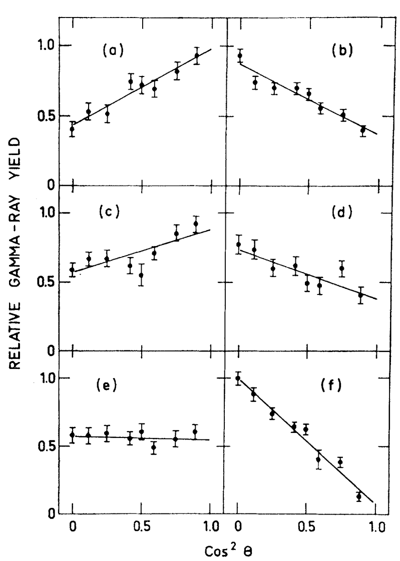

FIG. 8. Correlations for the reaction $C^{12}(He^3,p\gamma)N^{14}$ for the spin-1 levels of N^{14}. The correlations for the ground-state gamma rays from the 3.95-, 5.69-, and 6.21-MeV levels are shown in (a), (c), and (e), respectively, while the correlations for the 1.64-, 3.38-, and 3.90-MeV transitions to the first excited state are shown in (b), (d), and (f). The lines are the correlations according to the coefficients given in Table I. The correlations for the 3.95- and 6.21-MeV levels were obtained at a beam energy of 4.90-MeV and that for the 5.69-MeV level at a beam energy of 4.62 MeV.

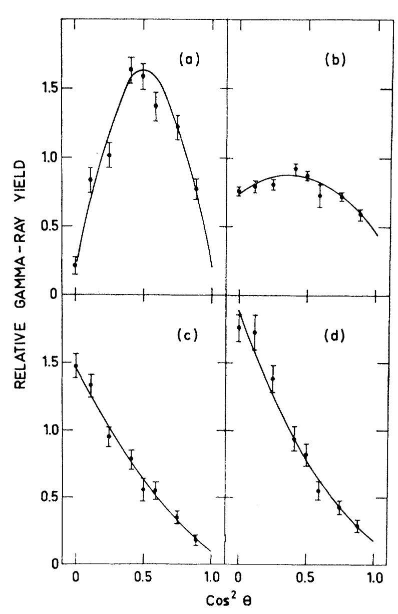

FIG. 9. Correlations for the reaction $C^{12}(He^3,p\gamma)N^{14}$ for the spin-2 levels of N^{14}. The correlations (a) and (b) are for the 5.10-MeV level for a bombarding energy of 4.90 MeV; (a) is for the 2.79-MeV transition to the first excited state and (b) is for the 5.10-MeV ground-state transition. The correlations (c) and (d) are for the ground-state transition from the 7.03-MeV level at beam energies 4.62 and 5.11 MeV, respectively. The lines are the correlations according to the coefficients given in Table I.

[16] P. F. Donovan, J. F. Mollenauer, and E. K. Warburton, Phys. Rev. **133**, B113 (1964).

[17] D. H. Wilkinson, Nucl. Spectry., **1962**, 852 (1960), Part B; E. K. Warburton, Phys. Rev. Letters **1**, 68 (1958).

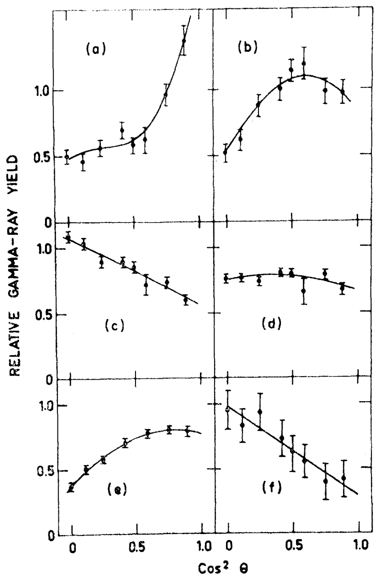

FIG. 10. Correlations for the reaction $C^{12}(He^3,p\gamma)N^{14}$ for the spin-3 levels of N^{14}. The first four correlations (a), (b), (c), and (d) are for the 5.83-MeV level for a bombarding energy of 4.90 MeV and are, respectively, the correlations for the 5.83-MeV → 0, 5.10-MeV → 2.31-MeV, 5.83-MeV → 5.10-MeV, and 5.10-MeV → 0 transitions. Correlations for the 6.44-MeV level at a bombarding energy of 5.46 MeV are shown in (e) and (f), where (e) is for the 6.44-MeV ground-state transition and (f) is for the 3.95-MeV → 2.31-MeV transition. The lines are for the correlations for the coefficients given in Table I except for (a) where the line also includes a P_6 (cosθ) term.

The 2.31-MeV Level

The 2.31-MeV level gamma rays were not studied directly in coincidence with protons to the first excited state, as the state has spin 0 and the correlations should always be isotropic. Many of the other states, however, decay to this level, particularly the 3.95-MeV second excited state. Accurate correlations were obtained for the 2.31-MeV gamma ray from the decay of the 3.95-MeV level and were used to confirm that the monitoring of the experiment was correct. The analysis of the result up to a_4 is given in Table I.

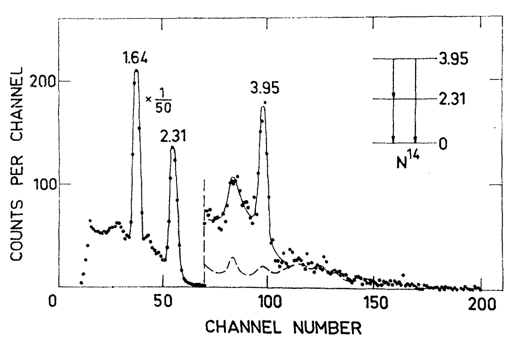

FIG. 11. Spectrum of gamma rays from the reaction $C^{12}(He^3,p\gamma)N^{14}$ in coincidence with protons to the 3.95-MeV level of N^{14}. The spectrum is the sum of the spectra recorded at eight angles for the experiments at 4.90-MeV He^3 energy. The total charge collected to obtain this spectrum was 9.6×10^{-3} C. The dashed line is the estimated spectrum of random coincidences.

The 3.95-MeV Level

The 3.95-MeV level decays predominantly by a $\Delta T=1$ transition to the 2.31-MeV state. The ground-state transition, a $\Delta T=0$ transition, is, however, more interesting, as this is an $M1$-$E2$ mixture where the strength of the $M1$ component should be weak. The intensity of this transition has been measured by Gove, Litherland, Almqvist, and Bromley[18] to be only 4% of the total decay of the 3.95-MeV state. If the angular correlation of this weak transition can be obtained simultaneously with the correlation of the pure $M1$ transition to the first excited state, then its mixing ratio can be deduced directly from the value of $F_2(11)/F_2(10)$.

This method of obtaining the mixing ratio will not succeed if the correlations are small. In theory the correlation of the 1.64-MeV gamma ray to the first excited state could have a value of a_2 varying from $+0.5$ to -1.0 corresponding to the extremes where only the $|m|=1$ and 0 substates are populated, respectively. If the m states are approximately equally populated the correlations will be almost isotropic and it would be difficult to determine an experimental value of $F_2(11)/F_2(10)$ sufficiently accurate to be useful. This difficulty never arose in practice. The values of a_2 for all four correlations of the 1.64-MeV gamma ray were close to -0.4 and were confined within a range of only 10% of that which is theoretically possible. The $m=0$ substate was always the more populated by a factor of about 3. This was a persistent feature of the correlations for the $C^{12}(He^3,p\gamma)N^{14}$ experiments, where without exception the $m=0$ substate was preferentially populated. This will be discussed more fully later.

For two bombarding energies, 4.62 and 4.90 MeV, usable correlations for the 3.95-MeV gamma ray were obtained. Because the intensity of the gamma ray was small, great care was taken in extracting the correlations for two reasons. Firstly the randoms are relatively more important and should be subtracted correctly, and secondly there is a substantial correction for the simultaneous detection of the 2.31- and 1.64-MeV gamma rays in the NaI crystal.

A spectrum of the gamma rays in coincidence with protons to the second excited state, obtained from the addition of the spectra at all eight angles for the experiment at a beam energy of 4.90 MeV, is shown in Fig. 11. The randoms which are shown by the dashed line in Fig. 11 were estimated by the procedure outlined in Sec. III. It can be seen that the randoms describe the higher energy part of the spectrum quite well, and therefore have been correctly estimated.

To correct for the simultaneous detection of the two

[18] H. E. Gove, A. E. Litherland, E. Almqvist, and D. A. Bromley, Phys. Rev. 103, 835 (1956).

TABLE I. Coefficients of the Legendre polynomials of the correlations for the $C^{12}(He^3,p\gamma)N^{14}$ and $C^{12}(He^3,\alpha\gamma)C^{11}$ reactions.

Level (MeV)	Gamma-ray energy (MeV) \ Beam energy (MeV)	4.62 a_2	4.62 a_4	4.90 a_2	4.90 a_4	5.11 a_2	5.11 a_4	5.46 a_2	5.46 a_4
3.95	2.31	+0.03±0.04	+0.03±0.05	−0.05±0.04	−0.06±0.05	+0.01±0.04	−0.09±0.05	+0.01±0.04	−0.06±0.06
	1.64	−0.33±0.04		−0.48±0.05		−0.39±0.04		−0.37±0.05	
	3.95	+0.50±0.09		+0.60±0.09					
4.91	4.91	+0.02±0.04	+0.00±0.06	−0.05±0.04	−0.07±0.05	−0.04±0.04	−0.12±0.06	+0.08±0.06	−0.04±0.08
5.10	2.79	+0.56±0.11	−0.48±0.14	+0.56±0.07	−1.30±0.10	+0.81±0.33	−1.04±0.46	+0.46±0.17	−0.94±0.24
	5.10	−0.03±0.04	−0.18±0.05	−0.11±0.04	−0.30±0.06	−0.13±0.09	−0.18±0.12	−0.10±0.05	−0.33±0.07
5.69	3.38	−0.39±0.10		−0.27±0.10				−0.14±0.06	
	5.69	+0.30±0.08		+0.07±0.07				+0.13±0.04	
5.83	0.73	−0.24±0.04	−0.04±0.06	−0.37±0.04	−0.01±0.05	−0.24±0.05	−0.03±0.06	−0.27±0.04	−0.04±0.05
	2.79	+0.74±0.22	−0.87±0.31	+0.48±0.08	−0.47±0.11	+0.51±0.12	−0.47±0.16	+0.47±0.11	−0.23±0.15
	5.10	+0.17±0.08	−0.27±0.10	−0.03±0.04	−0.09±0.05	+0.08±0.05	−0.20±0.06	−0.10±0.08	−0.16±0.10
	5.83	+0.81±0.12	+0.38±0.14	+0.85±0.10	+0.59±0.14	+1.00±0.10	+0.74±0.11	+0.96±0.08	+0.57±0.11
6.21	3.90	−0.14±0.06		−0.89±0.05		−0.34±0.09		−0.28±0.04	
	6.21	−0.05±0.08		−0.04±0.09		−0.02±0.11		+0.04±0.05	
6.44	1.64					−0.34±0.10		−0.61±0.16	
	6.44	+0.56±0.06	−0.37±0.09	+0.45±0.08	−0.47±0.10	+0.43±0.05	−0.37±0.06	+0.56±0.06	−0.26±0.08
7.03	7.03	−1.05±0.06	+0.14±0.08	−0.97±0.06	+0.06±0.05	−1.04±0.07	+0.18±0.07	−1.05±0.11	+0.25±0.12
C^{11}									
2.00	2.00	0.00±0.04	−0.04±0.05	−0.03±0.04	−0.04±0.05	−0.01±0.04	−0.05±0.05	+0.04±0.06	+0.10±0.10

gamma rays of the cascade, the resulting spectrum shape was computed from the spectrum shapes of the 1.64- and 2.31-MeV gamma rays. Then using the photofractions and efficiencies mentioned in Sec. III the correction was calculated for the window placed on the 3.95-MeV gamma ray. The most likely source of error is in the values of the photofractions. The correction changed the value of a_2 for the correlation of the 3.95-MeV gamma ray by about 1.5 times the error expected on the basis of statistics. Consequently, the values of the photofractions would have to be seriously in error before changing the conclusions arrived at, in these experiments.

A corrected correlation for the 3.95-MeV gamma ray and the corresponding correlation for the 1.64-MeV gamma ray are shown in Fig. 8. The ratios of the a_2 coefficients for the two correlations which can be compared with the theoretical values given by the function $F_2(11)/F_2(10)$ can be calculated from the values given in Table I and are $-(1.50\pm0.35)$ and $-(1.25\pm0.25)$ for the experiments at 4.62- and 4.90-MeV bombarding energy, respectively. The weighted mean of the two results is $-(1.35\pm0.30)$, where the error has been increased because of the greater likelihood of systematic errors for these correlations.

The function $F_2(11)/F_2(10)$ has been plotted against the mixing ratio in Fig. 12, where the sign of δ is correct for an $M1$-$E2$ mixture. The mixing ratios consistent with the experimental ratios lie in the ranges $-0.46\leqslant\delta\leqslant-0.19$ and $-5.2\leqslant\delta\leqslant-2.2$. These results are in excellent agreement with the recently published work of Riess, Trost, Rose, and Warburton,[19] who have used a similar method to obtain the mixing ratio. The ratio $F_2(11)/F_2(10)$ found experimentally by those authors was $-(1.4\pm0.3)$, corresponding to values of δ in the regions $-0.5\leqslant\delta\leqslant-0.2$ and $-5\leqslant\delta\leqslant-2$. Though they achieved greater statistical accuracy their experiments were performed at a bombarding energy where the correlations were less anisotropic, resulting in an overall accuracy similar to that of the present experiments.

The branching ratio for the ground-state transition was determined from the present results to be $(3.6\pm0.6)\%$, a figure which is in accord with that of $(3.8\pm0.5)\%$ given by Riess *et al.*[19]

The 4.91-MeV Level

Though the spin had not been confirmed experimentally, there are strong theoretical grounds for

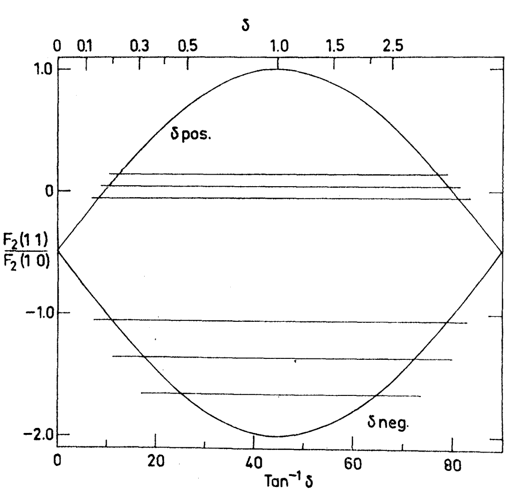

FIG. 12. Function $F_2(11)/F_2(10)$ plotted against mixing ratio δ. The experimental values, i.e., the ratio of the a_2 coefficients for the correlations of a spin $1\rightarrow1$ transition and a spin $1\rightarrow0$ transition, are shown with errors for the 3.95- and 6.21-MeV levels of N^{14} by the horizontal lines.

[19] F. Riess, W. Trost, H. J. Rose, and E. K. Warburton, Phys. Rev. **137**, B507 (1965).

believing that the level has spin and parity 0^-.[20–22] The correlations for the 4.91-MeV ground-state transition were all essentially isotropic, as can be seen from the example in Fig. 7 and the a_2 and a_4 coefficients listed in Table I. It cannot be proved from the correlation, however, that the spin is zero since isotropic or nearly isotropic correlations are possible for spins 1 and 2 under certain conditions. For spin 1, isotropic correlations are obtained if the m states are equally populated or, as will be discussed in the case of the 6.21-MeV level, if the mixing ratio is close to $+0.2$ or $+6.0$ (where the sign is correct for an $M1$-$E2$ mixture). The former condition is improbable, since for the other levels the nuclei were strongly aligned by the reaction. For spin 2, the values of a_2 and a_4 can be small for values of the mixing ratio close to $+6.0$ and -0.2 (where again the sign is for an $M1$-$E2$ mixture).

Transitions to the $T=0$ first excited state are relatively strong as a consequence of the isotopic-spin selection rule for $E1$ and magnetic transitions in self-conjugate nuclei. On the other hand, if the state has spin zero, a transition to the spin-zero first excited state would be rigorously forbidden. Such a transition, which would be conclusive evidence against spin zero, has been searched for. In Fig. 13 a gamma-ray spectrum in coincidence with protons to the 4.91-MeV level is shown. Besides the 4.91-MeV gamma ray no other peaks except those expected from random coincidences are seen. An upper limit of 1% can be placed on the branching ratio to the first excited state. This is again evidence for spin zero but does not exclude other possible spin assignments. Neither can a transition to the second excited state be seen. An upper limit of 0.5% can be placed on this possible branch.

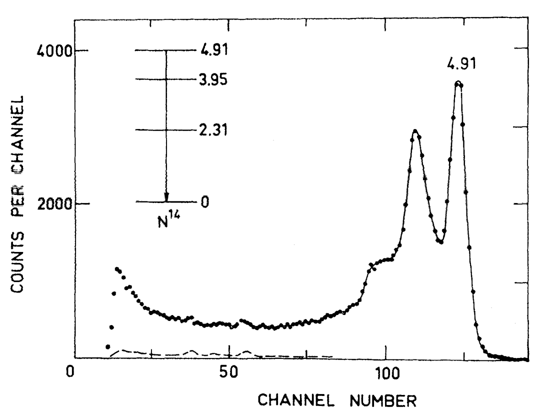

FIG. 13. Spectrum of gamma rays from the $C^{12}(He^3,p\gamma)N^{14}$ reaction in coincidence with protons to the 4.91-MeV level. The spectrum is the sum of the spectra recorded at eight angles at a bombarding energy of 4.90 MeV. The total charge collected to obtain this spectrum was 9.6×10^{-3} C. The estimated spectrum of random coincidences is shown by the dashed line.

The 5.10-MeV Level

The 5.10-MeV level is a 2^- state for which correlations were obtained for the ground-state transition, and for the 2.79-MeV transition to the first excited state. The $M2$, $\Delta T=1$ transition to the first excited state can compete with the $E1$ ground-state transition as a consequence of the isotopic-spin selection rule. The ground-state transition, an $E1$-$M2$-$E3$ mixture, as discussed by Warburton *et al.*,[20,22] is an unusual case where all three multipolarities may be significant, due to the inhibition of $E1$ and $M2$ transitions by the isotopic-spin selection rule and the possible enhancement of the $E3$ component. Blake, Jacobs, Newton, and Shapira,[23] in a work published during the course of the present experiments, demonstrated this to be so. Using a method similar to that described here, it was found that all three multipolarities influenced the correlations observed experimentally. At a He^3 bombarding energy of 4.9 they found that the correlation of the pure $M2$ transition to the first excited state was very strong corresponding to almost 100% population of the $m=0$ substate. For this reason the same beam energy was chosen for the final run in the present experiments. The 6.21-MeV level also showed strong correlations corresponding to almost complete population of the $m=0$ substate at this energy.

At 4.62-, 4.90-, and 5.46-MeV beam energies usable correlations were obtained for both the ground-state transition and the 2.79-MeV transition to the first excited state. The correlations for 5.11-MeV beam energy were so inaccurate that they have not been included in the analysis. The correlations for 4.90-MeV beam energy, which were the most accurate and the most pronounced, are shown in Fig. 9. The correlations at this energy were analyzed using the minimum χ^2-fit computer program, but the results for the 5.10- and 2.79-MeV transitions could not be simultaneously fitted for any value of the $E1$-$M2$ mixing ratio of the ground-state transition. Better fits, though still very poor fits, were obtained by supposing that the ground-state transition was an $E1$-$E3$ mixture. Good fits were only achieved by including all three multipolarities.

The a_2 and a_4 values for the correlation of the pure $M2$ transition to the first excited state corrected for the finite size of the gamma-ray counter are plotted with their errors as rectangles in Fig. 14. The triangle bounds the region of values theoretically possible. Each apex ABC represents 100% population of the $|m|=2$, 1, and 0 substates, respectively. The experimental points lie correctly close to the side BC of the triangle where the $|m|=2$ substate is only weakly populated. The points have a marked tendency to cluster in the apex C, where the $m=0$ substate is strongly populated. The finite-size

[20] E. K. Warburton, H. J. Rose, and E. N. Hatch, Phys. Rev. **114**, 214 (1959).
[21] W. W. True, Phys. Rev. **130**, 1530 (1963).
[22] E. K. Warburton and W. T. Pinkston, Phys. Rev. **118**, 733 (1960).
[23] R. S. Blake, D. J. Jacobs, J. O. Newton, and J. P. Shapira, Phys. Letters **14**, 219 (1965); Nucl. Phys. **71**, 113 (1965).

effect of the particle counter will tend to displace the experimental points away from the side BC towards the interior of the triangle. The dashed line has been calculated using the convention adopted for considering the finite-size effect, namely, $P(2)=0.05$, but the errors in the experimental points are too large to make any quantitative estimate of the effect. To demonstrate that the spin of the state is not 3 (spins less than 2 are ruled out by the a_4 term in the correlations) the line corresponding to BC for a $3\rightarrow 0$ transition is indicated by the line xy.

The ratio of the a_2 and a_4 coefficients for the correlations of the ground-state transition and the transition to the first excited state are compared with the theoretical values B_2 and B_4 in Fig. 15, where $B_k=F_k(21)/F_k(20)$. Two parameters occur in the theoretical values of $F_k(21)$, δ_{12} the dipole-quadrupole mixing ratio and δ_{13} the dipole-octupole mixing ratio. The formulas are given explicitly for an $E1$-$M2$-$E3$ mixture by Warburton, Lopes, Ollerhead, Poletti, and Thomas,[24] who have used the same sign convention as used here. The values of $F_k(20)$ are simply numbers, $F_2(20)=-0.5976$ and $F_4(20)=-1.0690$. The values of B_k have been calculated for the region within the limits given by Warburton, Alburger, Gallmann, Wagner, and Chase,[25] i.e., $\delta_{12}^2<0.2$ and $\delta_{13}^2<0.25$.

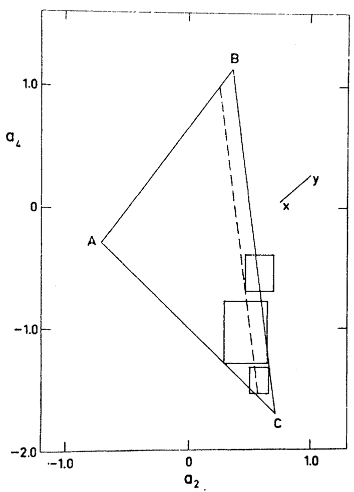

FIG. 14. Triangle bounding the region of a_2 and a_4 values theoretically possible for the correlation of a spin $2\rightarrow 0$ transition, where each apex corresponds to 100% population of $|m|=2$, 1, and 0 substates in the order ABC. The experimental values for the correlation of the 2.79-MeV transition in coincidence with protons to the 5.10-MeV level of N^{14} are shown as rectangles which lie close to the line BC as expected. The dashed line is for $P(2)=0.05$ showing how the finite size of the particle counter could change the correlations. The line xy has been calculated for a spin $3\rightarrow 0$ transition supposing that only the $|m|=1$ and 0 substates were populated.

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

[25] E. K. Warburton, D. E. Alburger, A. Gallmann, P. Wagner, and L. F. Chase, Phys. Rev. 133, B42 (1964).

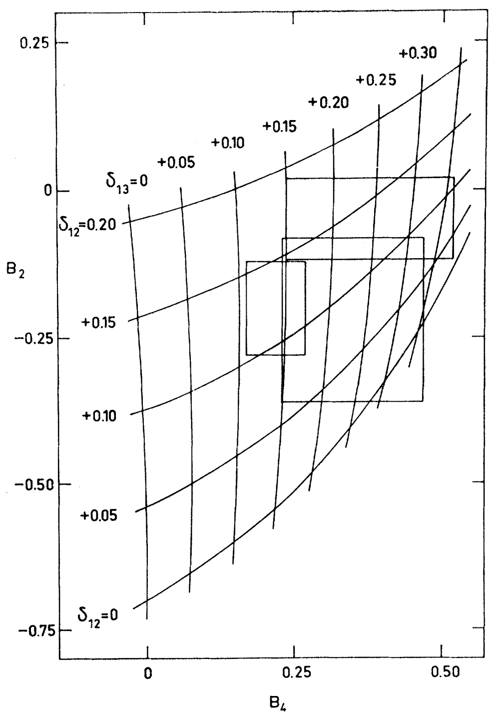

FIG. 15. Experimental values of B_2 and B_4, where B_k is the ratio of the a_k coefficients for the correlations of the 5.10- and 2.79-MeV transitions in N^{14}, compared with the theoretical values for an $E1$-$M2$-$E3$ mixture. The experimental results are shown by the rectangles. δ_{12} and δ_{13} are the dipole-quadrupole and dipole-octupole mixing ratios, respectively.

The experimental values of B_k given by the ratio of the a_2 coefficients for the correlations of the 5.10- and 2.79-MeV transitions are indicated with their errors by the rectangles in Fig. 15. Without using the limits given above three other solutions would have been possible.

Clearly, δ_{13} is required to explain the correlations. For $\delta_{13}=0$ the values of B_4 are always negative or zero, though experimentally the value was found to be positive for all the eight results available (there were 4 results from a study of the 5.83-MeV level which decays to the 5.10-MeV level). The evidence for δ_{12} was not so definite, but if the weighted mean of the three experimental points of Fig. 15 is taken, i.e., $B_2=-(0.13\pm0.06)$ and $B_4=+(0.26\pm0.04)$, this point lies at least three standard deviations from the line $\delta_{12}=0$. The weighted mean, given above, leads to mixing ratios of $\delta_{12}=+(0.14\pm0.03)$ and $\delta_{13}=+(0.16\pm0.03)$ which except for the difference in sign convention are in good agreement with the results of Blake *et al.*[23] It is noted that another experimental value of B_2 can be obtained from Ref. 26. This value, $B_2=-(0.30\pm0.10)$, would require a smaller mixing ratio δ_{12}, about $+0.08$.

The gamma-ray spectrum from the decay of the 5.10-MeV level, obtained by summing the results at 4.90-MeV He^3 beam energy, is shown in Fig. 16. Besides the ground-state transition and the cascade through

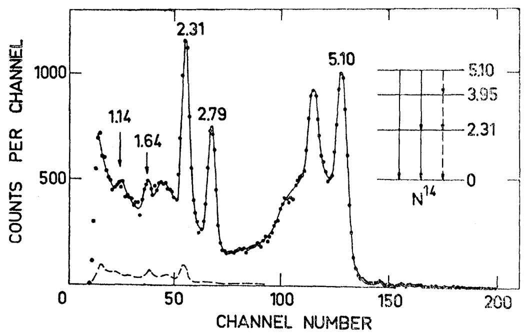

FIG. 16. Spectrum of gamma rays from the $C^{12}(He^3,p\gamma)N^{14}$ reaction in coincidence with protons to the 5.10-MeV level of N^{14}. The spectrum is the sum of the results for all eight angles for the experiment at a bombarding energy of 4.90 MeV. The total charge collected to obtain this spectrum was 9.6×10^{-3} C. The presence of a peak at 1.14 MeV and the height of the peak at 1.64 MeV suggest that a weak transition exists to the 3.95-MeV level.

the 2.31-MeV level a small peak is observed at (1.14±0.06) MeV which could arise from a transition to the 3.95-MeV level. In support of this possibility the peak at 1.64 MeV is observed to be more prominent than expected from the random coincidences. The same results were found from an examination of data at a He^3 beam energy of 5.46 MeV and there was some further confirmation from the results of the 5.83-MeV level which decays mainly to the 5.10-MeV level. The peaks are unlikely therefore to be due to another reaction, i.e., $O^{16}(He^3,p\gamma)F^{18}$. Though there is still some doubt as to the origin of the gamma ray, it is probably a transition to the 3.95-MeV level with an intensity (0.7±0.4)% of the total decay. The branching ratio of the transition to the 2.31-MeV level was measured to be (21±4)%, in good agreement with (25±3)% found by Warburton, Olness, Alburger, Bredin, and Chase[26] but is significantly smaller than the values given in Refs. 20 and 24.

The 5.69-MeV Level

This is a 1^- state for which correlations were obtained for the ground-state transition and the transition to the first excited state. The mixing ratio of the ground-state transition can therefore be obtained by the same method already discussed for the 3.95-MeV level. None of the correlations was very accurate. The strongest correlations observed, those at a bombarding energy of 4.62-MeV, are shown in Fig. 8. The ratio of the a_2 coefficients for the ground-state transition and the 3.38-MeV transition calculated from the values given in Table I gives a weighted mean of $-(0.58\pm0.20)$ which can be compared with the values of $F_2(11)/F_2(10)$ plotted in Fig. 12. Note that the signs for δ should be reversed as it concerns an $E1$-$M2$ mixture for the ground-state transition. The corresponding value for the mixing ratio $-(0.025\pm0.065)$ is small, as expected for an $E1$-$M2$ mixture. A very large value of the mixing ratio, the reciprocal of that given, is also possible from the experimental results. The result is in agreement with the value $+(0.03\pm0.03)$ previously determined.[26]

The intensities of the ground-state transition and the transition to the first excited state were measured as (36±4)% and (64±4)% in excellent agreement with other determinations.[26,27] Transitions to either the 3.95- or 4.91-MeV state are less than 2% of the total decay of the 5.69-MeV state.

The 5.83-MeV Level

Correlations for the 5.83-MeV level, which has spin and parity 3^-, were obtained for four gamma-ray transitions, the ground-state transition, the 0.73-MeV gamma ray to the 5.10-MeV state, and the ground-state and 2.79-MeV transitions from the 5.10-MeV level. The four correlations for a bombarding energy of 4.90 MeV are shown in Fig. 10. In principle, the 5.10-MeV transition could have been analyzed by the same method already discussed under the section dealing with the 5.10-MeV level. This has not been done because the results were not as accurate, and the correlations not as strong as found in the direct study of the level. They do confirm the previous findings illustrated in Fig. 15, that the value of B_2 is small and B_4 is positive.

The only pure transition for which correlations were obtained was the 2.79-MeV transition. The coefficients a_k of these correlations corrected for the finite size of the NaI crystal will be given by the expression $\rho_k(3)U_k(32)F_k(20)$. The function $U_k(32)$ contains the

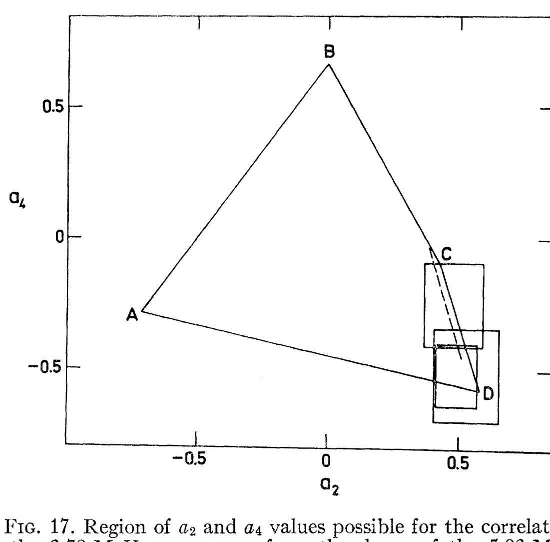

FIG. 17. Region of a_2 and a_4 values possible for the correlation of the 2.79-MeV gamma ray from the decay of the 5.83-MeV level. The points $ABCD$ correspond to 100% population of the $|m|=3$, 2, 1, and 0 substates, respectively, of the 5.83-MeV level. The experimental results are shown by the rectangles. The dashed line was calculated for $P(2)=0.05$, $P(3)=0.0$ as an indication of the finite-size effect of the particle counter.

[26] E. K. Warburton, J. W. Olness, D. E. Alburger, D. J. Bredin, and L. F. Chase, Phys. Rev. 134, B338 (1964).

[27] D. E. Alburger and E. K. Warburton, Phys. Rev. 132, 790 (1963).

mixing ratio of the preceding 0.73-MeV gamma ray, but as it contains no interference terms it is very insensitive to a small value of δ. The 0.73-MeV gamma ray is known to be mainly dipole[28] and it has been confirmed by a preliminary examination of the data that any quadrupole mixing is so small that its effect on $U_k(32)$ can be neglected to a high order of accuracy.

The values of a_2 and a_4 for the correlation of the 2.79-MeV gamma ray should lie in the region indicated in Fig. 17, where $ABCD$ corresponds to 100% population of the $|m|=3$, 2, 1, and 0 substates of the 5.83-MeV level, respectively. The experimental results for the three most accurate correlations which are represented by the rectangles lie along the line CD as expected. The dashed line was calculated for $P(2)=0.05$, $P(3)=0.0$ as an indication of the finite-size effect of the particle counter. The value of a_2 is seen to lie within fairly narrow limits. Since the coefficients for the correlations of all the gamma rays should be in constant ratio (see Sec. III) it follows that the a_2 values for the results for the 5.83-MeV level should be almost constant with bombarding energy. In general this is borne out by the results listed in Table I. There is a discrepancy in the result for the 0.73-MeV gamma ray at a bombarding energy of 4.90 MeV. The a_2 value is about three standard deviations higher than that expected from a study of all the other values and may be either a very improbable value or due to an undiscovered error. This result and the inaccurate results at a beam energy of 4.62 MeV have been dropped from the analysis of the 0.73-MeV gamma-ray correlations.

The mixing ratio for the 0.73-MeV gamma ray can be found by taking the ratio of the a_2 coefficients for the correlations of the 0.73- and 2.79-MeV gamma rays and comparing it with the calculated values of $F_2(32)/U_2(32)F_2(20)$. For the 2.79-MeV gamma ray the errors are large but it can be seen from Fig. 17 that they can be improved if the experimental values are constrained to lie close to the line CD. It has been assumed that the experimental values lie somewhere in the region between the line CD, where only the substates $|m|=1$ or 0 are populated, and the dashed line where this condition has been relaxed to include a 10% population of the $|m|=2$ substates. This assumption makes only a small change to the a_2 values, but the errors quoted can be considerably sharpened. The ratios of the a_2 coefficients for the two correlations are thus calculated to be $-(0.48\pm0.10)$ and $-(0.61\pm0.12)$ for the experiments at 5.11 and 5.46 MeV, respectively, leading to a weighted mean of $-(0.53\pm0.08)$. The experimental ratio is compared in Fig. 18 with the values of $F_2(32)/U_2(32)F_2(20)$ calculated for an $M1$-$E2$ mixture. Two solutions are obtained for the mixing ratio though the solution near $\delta\approx10$ can be eliminated since no large a_4 terms occur in the correlations of the 0.73-MeV gamma ray. The other solution $-(0.044\pm0.022)$ is in good agreement with a previous measurement[20] which found $\delta=-(0.045\pm0.045)$. It was not possible, however, to establish to a high degree of probability that the mixing ratio differs from zero.

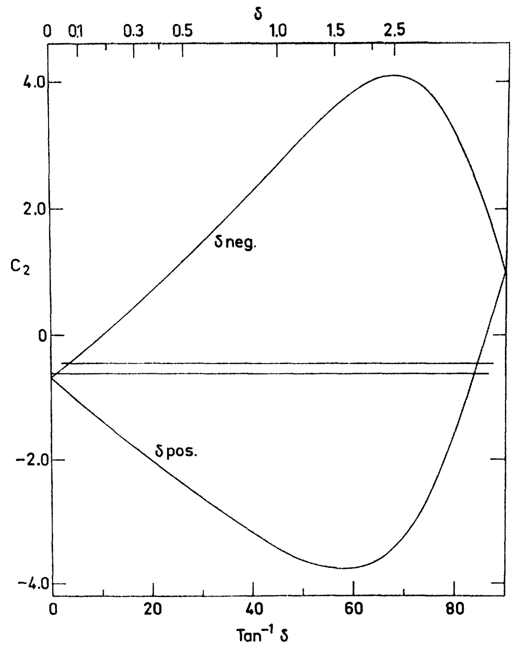

FIG. 18. Function C_2 plotted against the mixing ratio of the 0.73-MeV gamma ray from the 5.83-MeV level, where $C_2=F_2(32)/U_2(32)F_2(20)$. The experimental results, the ratio of the a_2 coefficients for the correlations of the 0.73- and the 2.79-MeV gamma rays, lie between the two horizontal lines.

The correlations for the ground-state transition, the 5.83-MeV gamma ray, were analyzed to terms in $P_6(\cos\theta)$. The a_6 coefficients were not very significant with respect to their errors but they were always positive. Positive values of a_6 indicate that it is the $m=0$ substate which is predominantly populated. The narrowest limits on the mixing ratio of the ground-state transition were obtained by considering the ground-state transition alone. The best correlation for this purpose was that for a He^3 bombarding energy of 5.11 MeV which, according to Table I, has the largest values of a_2 and a_4. The minimum χ^2 analysis of this correlation is shown in Fig. 19. The value of δ lies probably in the range $-2.6\leqslant\delta\leqslant-0.45$ and to a high degree of certainty lies in the range $-4.2\leqslant\delta\leqslant-0.37$. The dashed line calculated for $P(2)=0.05$ shows that it is not necessary to extend this range to allow for the finite size of the particle counter.

The mixing ratio of the 5.83-MeV gamma ray is in a region where the correlation changes very slowly as a function of δ. To obtain a more precise value of δ it would be necessary to measure very accurate correlations. Similar results, with wide limits on δ, have been obtained by other experiments.[20,24]

[28] J. A. Becker, Phys. Rev. **131**, 322 (1963).

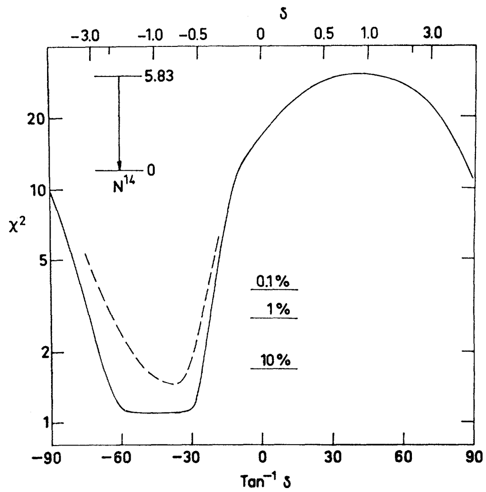

FIG. 19. Plot of the minimum χ^2 fit to the correlation of the 5.83-MeV transition at a He^3 energy of 5.11 MeV. For each value of the mixing ratio the minimum χ^2 compatible with only the $|m|=1$ and 0 substates populated has been determined supposing a spin $3\rightarrow 1$ transition and an $M2$-$E3$ mixture. The dashed line has been determined supposing $P(2)=0.05$. The percentages are the statistical probabilities that for the true value of the mixing ratio the value of χ^2 lies above the indicated values.

The relative intensities of the 5.83-MeV$\rightarrow$0 transition and the 5.83-MeV$\rightarrow$5.10-MeV transition were measured as $(29\pm4)\%$ and $(71\pm4)\%$, respectively, in agreement with the values $(25\pm5)\%$ and $(75\pm5)\%$ of Ref. 24 but in disagreement with the values of Ref. 20. No other mode of decay was noticed. An upper limit of 3% can be imposed on a transition to the first excited state and 1% on transitions to the 3.95- and 4.91-MeV states.

The 6.21-MeV Level

The 6.21-MeV level is a 1^+ state for which correlations were obtained for the ground-state transition and the 3.90-MeV transition to the first excited state. The mixing ratio of the ground-state transition can therefore be determined by the same method already employed for the 3.95- and 5.69-MeV states.

Like the 5.10-MeV level at the same bombarding energy, the 6.21-MeV state was aligned almost completely in the $m=0$ substate at a He^3 energy of 4.90 MeV. This was fortunate as the results obtained at this energy are so accurate compared with the others that they alone have been used to determine the mixing ratio of the ground-state transition. The correlations of the ground-state transition and the 3.90-MeV gamma ray to the first excited state are shown in Fig. 8. The extreme alignment of the 6.21-MeV level is indicated by the near zero yield of the 3.90-MeV gamma ray at 0°. For all four experiments the 6.21-MeV gamma ray was isotropic within the experimental errors. This can happen for values of the mixing ratio near +5.8 and +0.18 where $F_2(11)/F_2(10)$ passes through zero.

The ratio of the a_2 coefficients for the two correlations at a bombarding energy of 4.90 MeV is $+(0.045\pm0.10)$. The corresponding values of the mixing ratio obtained for an $M1$-$E2$ mixture from Fig. 12 are $+(0.19\pm0.04)$ or $+4.4\leqslant\delta\leqslant+6.6$ and to a high degree of certainty the value of δ lies in the ranges $+0.04\leqslant\delta\leqslant+0.33$ and $+2.9\leqslant\delta\leqslant+24.0$. Gallmann[29] has previously shown that the value of δ is positive and is either very large or very small.

The intensities of the 6.21- and the 3.90-MeV gamma rays were measured to be $(21\pm3)\%$ and $(79\pm3)\%$, respectively, in good agreement with earlier work.[26] Decays to the 3.95-, 4.91-, and 5.10-MeV levels are less than 1% of the total.

The 6.44-MeV Level

The 6.44-MeV level has spin and parity 3^+ though spins 2 and 4 also fitted the correlations of the present experiment. The state decays mainly to the ground state with weaker transitions to the 3.95- and 5.10-MeV levels. The $E2$ transition strengths for the first two gamma rays and the $E1$ transition strength to the 5.10-MeV excited state are known from the lifetime of the 6.44-MeV level.[30] It is expected that the mixing ratio for any magnetic multipolarity will be immeasurably small.

The spectrum of gamma rays in coincidence with protons to the 6.44-MeV level is shown in Fig. 20 and was obtained by adding together the results for the experiment at a bombarding energy of 5.46 MeV. Besides the transition to the ground state, gamma rays of 2.49, 2.31, and 1.64 MeV can be seen from the cascade through the 3.95-MeV level. Only the presence of a 1.34-MeV gamma ray confirms the existence of a transition to the 5.10-MeV state. The 5.10- and 2.79-MeV gamma rays which should also be present are too weak to be distinguished.

Correlations were obtained for the 6.44-MeV transition at all four bombarding energies, but correlations

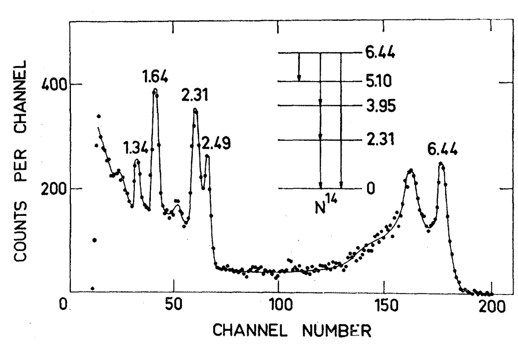

FIG. 20. Spectrum of gamma rays in coincidence with protons from the $C^{12}(He^3,p\gamma)N^{14}$ reaction to the 6.44-MeV level. The spectrum is the sum of the experimental results at a He^3 energy of 5.46 MeV. A total charge of 4.2×10^{-3} C was collected to obtain this spectrum.

[29] A. Gallmann, Ann. Phys. (Paris) 4, 185 (1959).
[30] J. A. Becker and E. K. Warburton, Phys. Rev. **134**, B349 (1964).

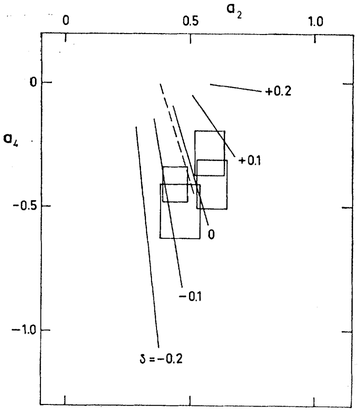

FIG. 21. Experimental results for the a_2 and a_4 coefficients for the correlations of the 6.44-MeV transition of N^{14} are shown by the rectangles. Lines calculated for fixed values of the $E2$-$M3$ mixing ratio, supposing a spin $3 \rightarrow 1$ transition and that only the $|m|=1$ and 0 substates are populated, are shown. The calculated values for $P(2)=0.05$, $P(3)=0.0$, for $\delta=0$ are shown by the dashed line demonstrating that the finite-size effect of the particle counter is small in this case.

for the other transitions were generally too inaccurate to be of use. At two energies correlations were obtained for the 1.64-MeV transition. The correlations for the two transitions at a He^3 energy of 5.46 MeV are shown in Fig. 10. The 2.49-MeV gamma-ray to the 3.95-MeV level should, like the ground-state transition, be $E2$ with a negligible component of $M3$. Its correlation therefore, should be identical to that of the ground-state transition. Within the limited accuracy with which the intensities of the 2.49-MeV gamma ray could be determined this appeared to be true.

The values of a_2 and a_4 have been calculated for the correlation of the ground-state transition for fixed values of the mixing ratio assuming that only the $|m|=1$ and 0 substates were populated. For each value of δ the possible values of a_2 and a_4 are represented by the straight lines shown in Fig. 21, where the sign of δ is correct for an $E2$-$M3$ mixture. The experimental points are represented by the rectangles in Fig. 21 which cluster about the line for $\delta=0$. The dashed line has been calculated for $\delta=0$ with the assumption that $P(2)=0.05$, to show that the finite-size effect of the particle detector is not very important in this case. In principle a second region fits the experimental data where δ has a value of about -4.0, but corresponds to an $M3$ transition strength of about 10^5 Weisskopf units. It can thus be concluded that the mixing ratio is not measurably different from zero, and is probably less than 0.05.

There is little information to be obtained from the correlation of the 1.64-MeV gamma ray except that δ^2 for the preceding 2.49-MeV transition is small and probably less than 0.25. For small values of δ^2, values of a_2 for the correlation of the 1.64-MeV gamma ray should lie between -0.4 and -0.3. For larger values of δ^2 these limits move towards positive values.

The intensities of the transitions to the ground state and to the 3.95- and 5.10-MeV states were measured to be $(74\pm4)\%$, $(19\pm4)\%$, and $(7\pm2)\%$, respectively. Though the first two values are in good agreement with the results of Ref. 26, the present result for the 1.34-MeV transition is smaller by a factor of two. It has been assumed that the 1.34-MeV gamma ray is pure $E1$ in which case its angular correlation should be the same as the correlation of the 1.64-MeV gamma ray. The intensity of the two transitions can therefore be compared directly in Fig. 20 where the 1.64-MeV gamma ray appears to be at least twice as intense as the 1.34-MeV gamma ray. The branch to the 5.83-MeV level is estimated as less than 2% of the total.

The 7.03-MeV Level

The 7.03-MeV level has spin and parity 2^+ and decays predominantly to the ground state. Since the correlation of the ground-state transition depends on two parameters, the $M1$-$E2$ mixing ratio will be determined more accurately if terms higher than $P_2(\cos\theta)$ occur in the correlations. Terms in $P_4(\cos\theta)$ are possible from the quadrupole component and will be measurable provided that the mixing ratio is not too small.

Two examples of the correlations of the 7.03-MeV gamma ray, those found for the bombarding energies of 4.62 and 5.11 MeV are shown in Fig. 9. Small positive values of a_4 were found for all experimental correlations. The a_4 are not very large compared with their errors, but so strong were the correlations that when they were fitted to only $P_2(\cos\theta)$ near zero or negative intensities were predicted at 0°.

The mixing ratio has been found by the same method employed for the 6.44-MeV gamma ray. The experimental values of a_2 and a_4 are compared in Fig. 22 with theoretical predictions. Only one region fitted the experimental results. The mixing ratio certainly lies within the limits $+0.2 \leqslant \delta \leqslant +1.1$, and to one standard

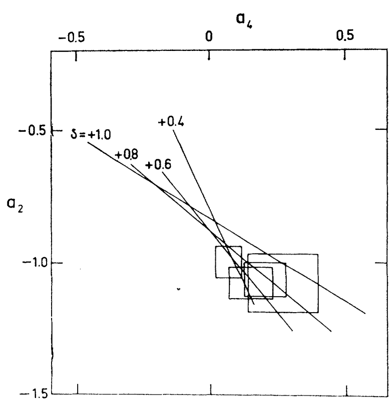

FIG. 22. Experimental results for the a_2 and a_4 coefficients for the correlation of the 7.03-MeV transition of N^{14} are shown by the rectangles. The lines shown have been calculated for fixed values of the $M1$-$E2$ mixing ratio, supposing a spin $2 \rightarrow 1$ transition and that the $|m|=1$ and 0 substates only are populated.

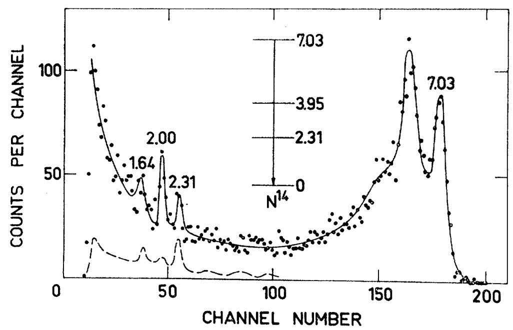

FIG. 23. Spectrum of gamma rays from the $C^{12}(He^3,p\gamma)N^{14}$ reaction in coincidence with protons to the 7.03-MeV level obtained by the addition of the spectra for the eight angles for the experiment at a bombarding energy of 4.90 MeV. The dashed line is the estimated random coincidence spectrum. The 2.00-MeV gamma rays are from the first excited state of C^{11} produced in the reaction $C^{12}(He^3,\alpha\gamma)C^{11}$. A total charge of 9.6×10^{-3} C was collected to obtain this spectrum.

deviation it has the value $+(0.6\pm0.2)$. The absolute value of the mixing ratio is in very good accord with the value 0.6 ± 0.1 found by Prosser, Krone, and Singh.[31]

Poorer fits were obtained when it was supposed that $P(2)=0.05$ since then the experimental values of a_2 and a_4 lie largely outside the region theoretically possible. This is the clearest evidence from the present work that the value 0.05 for $P(2)$ overestimated the finite-size effect.

The addition of the gamma-ray spectra in coincidence with protons to the 7.03-MeV level for the experiment at a beam energy of 4.90 MeV is shown in Fig. 23. A $(9\pm5)\%$ branch to the 3.95-MeV level has been reported.[24] The resulting 3.08-, 1.64-, and 2.31-MeV gamma rays have not been seen in this experiment. The 1.64- and 2.31-MeV gamma rays appearing in Fig. 23 are present only to the degree expected from the random coincidences. The 2.00-MeV gamma rays are due to the nearby alpha-particle group to the first excited state of C^{11} (see Fig. 1). Branches to the 3.95- and the 2.31-MeV states were estimated as less than 2% and 3%, respectively, the intensity of the ground-state transition, branches to the 5.10- and 4.91-MeV levels less than 4%, and branches to each of the other states up to and including the 6.21-MeV level, less than 2%.

The 2.00-MeV Level of C^{11}

The bombarding energies were too low to study any other than the 2.00-MeV level of C^{11} excited in the reaction $C^{12}(He^3,\alpha\gamma)C^{11}$. All four correlations obtained for this state were isotropic as shown by the example in Fig. 7 and the coefficients listed in Table I. As discussed by Warburton *et al.*[24] this is no proof that the spin of the state is $\frac{1}{2}$, since for particular values of the mixing ratio spins of $\frac{3}{2}$ and $\frac{5}{2}$ will also fit the results.

[31] F. W. Prosser, R. W. Krone, and J. J. Singh, Phys. Rev. **129**, 1716 (1963).

VI. THE $C^{12}(d,p\gamma)C^{13}$ REACTION

An attempt was made to obtain the mixing ratio of the $M2$-$E3$ ground-state transition from the 3.85-MeV level of C^{13} excited by the reaction $C^{12}(d,p\gamma)C^{13}$. The mixing ratio was determined from the angular correlation of the ground-state transition in coincidence with protons to the 3.85-MeV level. The main difficulty in determining the correlation was that the 3.85- and 3.68-MeV gamma rays which result from the decay of the level studied were poorly resolved in the gamma-ray spectra. The correlation of the 3.85-MeV gamma ray was measured twice at a beam energy of 3.98 MeV and the mean values of a_2 and a_4 were found to be $+(0.43\pm0.06)$ and $-(0.43\pm0.08)$, respectively. In Fig. 24 the result of the analysis by the minimum χ^2-fit computer program for a spin-$\frac{5}{2}$ to spin-$\frac{1}{2}$ transition is shown. Four minima are seen for values of δ of -4.3, -0.65, $+0.1$, and $+2.1$ but reasonably good fits to the data are obtained for large regions of values of the mixing ratio.

The ratio of the intensity of the 3.68- to the 3.85-MeV gamma rays was measured to be 0.59 ± 0.07. Including the 1% decay to the 3.09-MeV level the percentage decay to the 3.68-MeV level and the ground state are $(37\pm4)\%$ and $(62\pm4)\%$, respectively. These values are in poor agreement with the corresponding values

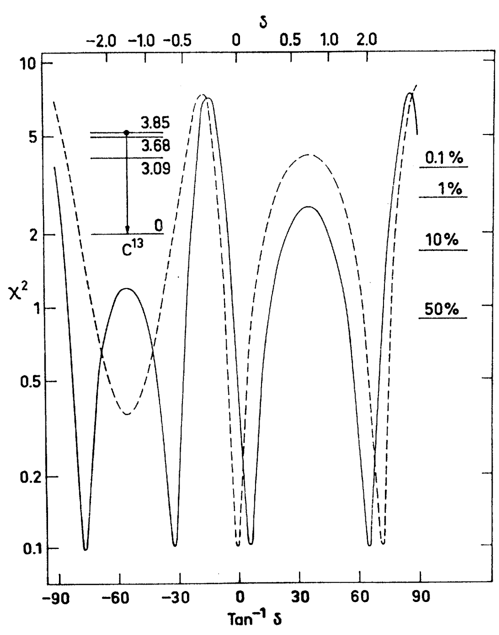

FIG. 24. Minimum χ^2 fits to the correlation of the ground-state transition in coincidence with protons to the 3.85-MeV level of C^{13} from the reaction $C^{12}(d,p\gamma)C^{13}$. The curve, calculated for a spin-$\frac{5}{2}$ to spin-$\frac{1}{2}$ transition, is plotted against the $M2$-$E3$ mixing ratio. The full line supposes that only the $|m|=\frac{1}{2}$ and $\frac{3}{2}$ substates are populated while the dashed line includes a small population of the $|m|=\frac{5}{2}$ substates $[P(\frac{5}{2})=0.05]$ to show the effect of the finite size of the particle counter. The percentages are the statistical probabilities that for the true value of the mixing ratio the value of χ^2 lies above the indicated values.

TABLE II. Radiative widths for transitions from the 5.10-MeV level of N^{14}.

Gamma ray (energy in MeV)	Multipolarity	Γ observed (eV)	Γ calculated[a] (eV)
5.10 → 0	*E*1	1.4×10^{-4} [b]	...
5.10 → 0	*M*2	2.7×10^{-6} [b]	1.7×10^{-5}
5.10 → 0	*E*3	$(3.5\pm0.4)\times10^{-6}$ [c]	0.8×10^{-5}
5.10 → 2.31	*M*2	3.8×10^{-5} [b]	7.8×10^{-5}
5.10 → 3.95	*E*1	1.3×10^{-6} [d]	...

[a] Calculated values taken from Ref. 22.
[b] Probable error of the order of 50%.
[c] Value obtained from the electron-scattering results of Ref. 34.
[d] Requires further experimental verification.

TABLE III. Relative population of the $|m|=0$ and 1 substates of the N^{14} levels, $P(0)/P(1)=x$.

Level (MeV) \ Beam energy (MeV)	4.62	4.90	5.11	5.46
3.95	2.55±0.3	3.9±0.6	3.0±0.4	2.9 ±0.4
5.10	3.0 ±0.8	>12	>2	12>*x*>4
5.69	3.0 ±1.0	2.2±0.6	1.5±0.5	1.5 ±0.25
5.83	>2	>2	>2	>1.5
6.21	1.5 ±0.25	>20	2.6±0.7	2.25±0.25
6.44	>1	>1	>1	>1
7.03	>3.5	>2	>3.5	>3

(24±5)% and (75±5)% determined in a previous experiment.[32]

VII. DISCUSSION

The results obtained for the O^{15} nucleus can be compared with results of Warburton *et al.*,[24] for the mirror nucleus N^{15}. The single-particle transition probabilities for magnetic multipoles contain the magnetic moment of the jumping nucleon which can be positive or negative according to whether the nucleon is a proton or a neutron. Thus, provided there is no sign change for *E*2 or *E*3 also, the *M*1-*E*2 and *M*2-*E*3 mixing ratios for gamma-ray transitions between mirror levels are expected, on the average, to be similar in magnitude but to differ in sign. This sign change is illustrated in the case of the 6.33-MeV level of N^{15} where the mixing ratio was measured[14] as $+(0.13\pm0.02)$ in comparison with $-(0.19_{-0.07}^{+0.04})$ found for the 6.16-MeV level of O^{15}. (It will be assumed that the smaller of the two possible experimental values is the correct one.) Similarly, the mixing ratio for the 5.28-MeV level of N^{15} was measured[24] as $-(0.15\pm0.06)$ in comparison with the value $+(0.035_{-0.04}^{+0.11})$ obtained for the 5.24-MeV level of O^{15}. In the latter case it only appears probable, from the experimental results, that there is a change of sign. A small correction for the size of the particle counter would, however, shift the O^{15} result towards higher positive values.

Rose and Lopes[33] have stated that the absolute sign of the mixing ratios of the 6.33-MeV level of N^{15} and the mirror level of O^{15} are not given correctly by theory if it is assumed that these states are formed by a $p_{3/2}$ hole in an O^{16} core. This has led these authors to suggest that the states would be better described as a $P_{1/2}$ hole in the 2^+, 6.92-MeV state of O^{16}.

Partial radiative widths, Γ(*E*2) or Γ(*E*3), for the ground-state transitions from the 3.95-, 5.10-, 5.83-, and 7.03-MeV levels of N^{14} have been deduced from the electron-scattering data of Bishop, Bernheim, and Kossanyi-Demay[34] and were found to be in reasonably good agreement with the calculations of Warburton and Pinkston.[22] Further comparison with these calcu-

TABLE IV. Mixing ratios of the gamma-ray transitions in the nuclei O^{15} and N^{14}.

Nucleus	Level (MeV)	Gamma ray (MeV)	Multipolarities	Mixing ratio	Observations
O^{15}	5.24	5.24	*M*2-*E*3	$+(0.035_{-0.04}^{+0.11})$, $+(2.5_{-0.6}^{+0.8})$	Assumed isotropic contribution from 5.18-MeV level
	6.16	6.16	*M*1-*E*2	$-(0.19_{-0.07}^{+0.04})$, $+(2.9_{-0.5}^{+1.1})$	
N^{14}	3.95	3.95	*M*1-*E*2	$-0.46\leqslant\delta\leqslant-0.19$	
				$-5.2\leqslant\delta\leqslant-2.2$	
	5.10	5.10	*E*1-*M*2	$+(0.14\pm0.03)$	
			*E*1-*E*3	$+(0.16\pm0.03)$	
	5.69	5.69	*E*1-*M*2		No evidence for a mixing ratio different from zero
	5.83	0.73	*M*1-*E*2	$-(0.044\pm0.022)$	
		5.83	*M*2-*E*3	$-2.6\leqslant\delta\leqslant-0.45$	
	6.21	6.21	*M*1-*E*2	$+0.19\pm0.04$	
				$+4.4\leqslant\delta\leqslant+6.6$	
	6.44	2.49	*E*2-*M*3		No evidence for a mixing ratio different from zero
		6.44	*E*2-*M*3		No evidence for a mixing ratio different from zero
	7.03	7.03	*M*1-*E*2	$+(0.6\pm0.2)$	

[32] R. J. Mackin, W. R. Mills, and J. Thirion, Phys. Rev. **102**, 802 (1956).
[33] H. J. Rose and J. S. Lopes, Phys. Letters **18**, 130 (1965).
[34] G. R. Bishop, M. Bernheim, and P. Kossanyi-Demay, Nucl. Phys. **54**, 353 (1964).

lations can be made using the experimental mixing and branching ratios. As Riess *et al.* have discussed,[19] the magnitude of the $M1$-$E2$ mixing ratio for the 3.95-MeV transition is expected to be about 3, within one of the two regions, $-5.2 \leqslant \delta \leqslant -2.2$, determined experimentally. The partial width $\Gamma(E2)$ from the electron-scattering work for the transition is $(4.8\pm0.3)\times10^{-3}$ eV. Combining these results with the branching ratio $(3.6\pm0.6)\%$ for the 3.95-MeV level the radiative width of the $M1$, 3.95 MeV$\rightarrow$2.31-MeV, transition is found to be (0.145 ± 0.03) eV. This width is in good agreement with the values calculated by Warburton and Pinkston, 0.095, 0.16, and 0.13 eV, where the first was calculated supposing extreme jj coupling and the latter two intermediate coupling with a tensor force included, as explained in Ref. 22. For the values of the mixing ratio within the limits $-0.46 \leqslant \delta \leqslant -0.19$, the other region consistent with the experimental results, the width $\Gamma(M1)$ for the 1.63-MeV gamma ray would be at least 0.6 eV, i.e., greater than 6 Weisskopf units.

The electron-scattering results predict a value of $(3.5\pm0.4)\times10^{-6}$ eV for the value of $\Gamma(E3)$ for the 5.10-MeV transition. As Bishop[35] has recently discussed $\Gamma(E1)$ and $\Gamma(M2)$ can also be obtained from the $E1$-$E3$ and $E1$-$M2$ mixing ratios. These values, as well as $\Gamma(M2)$ for the 2.79-MeV transition to the first excited state, and $\Gamma(E1)$ for the possible transition to the second excited state, have been estimated using the present results and are listed in Table II where they are compared with the calculated widths of Ref. 22. The calculated widths are several times larger than the observed widths but the accuracy of the observed widths is rather poor. There are no calculated values for the two isotopic-spin forbidden $E1$ transitions which are of the order 10^4 times slower than average allowed $E1$ transitions. The total radiative width 1.8×10^{-4} eV corresponds to a mean lifetime of about 4×10^{-12} sec, well within the lower limit of 3×10^{-13} sec set by Doppler-shift measurements.[20]

In the case of the 5.83-MeV transition of N^{14} accurate comparisons with theory cannot be made since the $E3$-$M2$ mixing ratio is only known with wide experimental limits. The width $\Gamma(E3)$ obtained from the electron-scattering data is $(0.93\pm0.05)\times10^{-5}$ eV. If this is combined with the lower limit on the mean lifetime of the 5.83-MeV state, i.e., 2.3×10^{-12} sec,[30] and the branching ratio measured in the present experiments a lower limit on the mixing ratio $|\delta| \geqslant 0.3$ is found in agreement with the region $-0.45 \geqslant \delta \geqslant -2.6$ determined from the angular correlations. For the 5.83-MeV$\rightarrow$5.10-MeV transition a lower limit $\Gamma(M1) \geqslant 1.9\times10^{-5}$ eV can be deduced from the electron-scattering data and the present results. An upper limit $\Gamma(M1) \leqslant 2.2\times10^{-4}$ eV can be determined from the lifetime measurement. The extreme jj coupling calculation of Warburton and Pinkston for $\Gamma(M1)$ has a value of 1.8×10^{-5} eV, which is very close to the lower limit. The $M1$-$E2$ mixing ratio of the 0.73-MeV transition is calculated to have a magnitude $\delta=0.12$, which is certainly larger than the experimental value $-(0.044\pm0.022)$.

[35] G. R. Bishop, Phys. Letters **17**, 311 (1965).

TABLE V. Gamma-ray branching ratios for the bound states of N^{14}.

E_i (MeV)	E_f (MeV)	E_γ (MeV)	Present results	Other results	Average
3.95	0	3.95	3.6±0.6	3.7±0.6[a]; 3.8±0.5[b]	3.7±0.3
3.95	2.31	1.64	96.4±0.6	96.3±0.6[a]; 96.2±0.5[b]	96.3±0.3
4.91	0	4.91	100	100[a]; 98[c]	99.5±0.5
4.91	2.31	2.60	<1	0.4±0.7[c]	<1
4.91	3.95	0.96	<0.5	1.3±1[c]	0.5±0.5
5.10	0	5.10	79 ±4	67[a]; 68 ±4[d]; 75 ±3[e]; 71 ±5[f]	74 ±3
5.10	2.31	2.79	21 ±4	33[a]; 32 ±4[d]; 25 ±3[e]; 29 ±5[f]	26 ±3
5.10	3.95	1.15	(0.7±0.4)		(0.7±0.4)
5.69	0	5.69	36 ±4	37[a]; 37 ±2[g]; 40 ±3[e]	38 ±2
5.69	2.31	3.38	64 ±4	63[a]; 63 ±2[g]; 60 ±3[e]	62 ±2
5.69	3.95	1.74	<2		<2
5.69	4.91	0.78	<2		<2
5.83	0	5.83	29 ±4	15[a]; 16 ±4[d]; 25 ±5[f]	23 ±4
5.83	2.31	3.52	<3		<3
5.83	3.95	1.88	<1		<1
5.83	4.91	0.92	<1		<1
5.83	5.10	0.73	71 ±4	85[a]; 84 ±4[d]; 75 ±5[f]	77 ±4
6.21	0	6.21	21 ±3	24[a]; 24 ±3[e]	23 ±2
6.21	2.31	3.90	79 ±3	76[a]; 76 ±3[e]	77 ±2
6.21	3.95	2.26	<1		<1
6.21	4.91	1.30	<1		<1
6.21	5.10	1.11	<1		<1
6.44	0	6.44	74 ±4	100[a]; 70[h]; 65 ±3[e]	69 ±3
6.44	3.95	2.49	19 ±4	(30)[h]; 21 ±2[e]	21 ±2
6.44	5.10	1.34	7 ±2	14 ±3[e]	10 ±3
6.44	5.83	0.61	<2	<3[e]	<2
7.03	0	7.03	100	(100)[a]; 91 ±4[f]	97 ±3
7.03	2.31	4.72	<3	<5[f]	<3
7.03	3.95	3.08	<2	9 ±5[f]	3 ±3
7.03	4.91	2.12	<4		<4
7.03	5.10	1.93	<4		<4
7.03	5.69	1.34	<2		<2
7.03	5.83	1.20	<2		<2
7.03	6.21	0.88	<2		<2

[a] F. Ajzenberg-Selove and T. Lauritsen, Nucl. Phys. **11**, 1 (1959).
[b] Reference 19.
[c] Reference 23.
[d] Reference 20.
[e] Reference 26.
[f] Reference 24.
[g] Reference 27.
[h] H. J. Rose, Nucl. Phys. **19**, 113 (1960).

Though the relative populations of the magnetic substates of the N^{14} levels were primarily only regarded as parameters to be eliminated, there is some interest in their values, for as Goldfarb[36] has pointed out, they can give an indication of the reaction mechanism. If the mechanism is predominantly compound nuclear it would not be expected that any one substate would be preferentially populated for all bombarding energies.

Experimentally, however, it was found that the $m=0$ substate was strongly populated relative to the $|m|=1$ substates, indicating that, at the backward angles, a direct interaction is contributing significantly to the reaction.

The population parameters $[=P(0)/P(1)]$ are listed in Table III. For the levels with spin 1 and the 5.10-MeV level the parameter can be directly determined from the correlation of the transition to the first excited state. For the other levels an attempt has been made to estimate the population parameters though only rough limits can be given to the values with a reasonable degree of probability. Seven excited states of N^{14} with nonzero spin have been studied at four different bombarding energies. In all the 28 resulting cases there is not one instance where there is any evidence that the value of the population parameter was less than 1. The values demonstrate the strong preference that exists for the $m=0$ substate.

The proton angular distributions of the $C^{12}(He^3,p)N^{14}$ reaction show features of both compound-nuclear and direct processes.[15,37] At bombarding energies near 3 MeV the process is principally compound nuclear but around 5 MeV where the present experiments were conducted the distribution cannot be simply interpreted and it may be that this is in an intermediate region where the compound-nuclear and direct processes compete with similar amplitudes. The suggestion by El Nadi and El Khishin[38] that the persistent backward peaking seen in this reaction is due to heavy-particle stripping is in accord with experiment for two reasons. Firstly, in these experiments the protons were detected near 180°, where the effect due to normal stripping should be small but the effect due to heavy-particle stripping is near a maximum. Secondly, the evidence for a direct interaction is as marked for the 3.95- and 7.03-MeV states as it is for the others. These two states are believed to have largely a $(p_{3/2}^{-1}p_{1/2}^{-1})$ configuration.[21] This core-excited configuration would not be readily excited by normal stripping but could be excited by a heavy-particle stripping process where the outgoing proton comes from the C^{12} core. This second argument, however, is not a very strong one, since the ground state of C^{12} is not a pure $p_{3/2}^{8}$ configuration,[39] and so the $C^{12}(He^3,p)N^{14}$ reaction could proceed, for example, through $p_{3/2}^{6}p_{1/2}^{2}\rightarrow p_{3/2}^{7}p_{1/2}^{3}$.

It was fortunate experimentally that the $m=0$ substate was strongly populated since the most extreme correlations result from this condition. In experiments of this nature it would be normally advantageous therefore to choose conditions in which there was an important direct interaction.

VIII. CONCLUSION

Gamma-ray transitions in the nuclei O^{15}, N^{14}, and C^{13} have been studied by particle-gamma angular-correlation measurements. All results for the mixing ratios of the gamma-ray transitions are listed in Table IV where the errors are given to one standard deviation and where necessary include an uncertainty due to the finite size of the particle counter. Branching ratios measured for the N^{14} levels are compared with previous results in Table V.

ACKNOWLEDGMENTS

The authors wish to express their appreciation of the contacts they have had with the group at the Brookhaven National Laboratory, particularly to Dr. D. E. Alburger who worked with us during the $C^{12}(d,p\gamma)C^{13}$ experiment, and to Dr. E. K. Warburton for the interest he has shown in the work.

[36] L. J. B. Goldfarb, Nucl. Phys. **57**, 4 (1964).
[37] S. Hinds and R. Middleton, Proc. Phys. Soc. (London) **75**, 745 (1960).
[38] M. El Nadi and M. El Khishin, Proc. Phys. Soc. (London) **73**, 705 (1959).
[39] D. Kurath, Phys. Rev. **101**, 216 (1956).