Electromagnetic Decay of the N^{14} 3.95- and 7.03-MeV Levels*

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The $C^{12}(He^3,p\gamma)N^{14}$ reaction has been used to study the electromagnetic decay of the 3.95- and 7.03-MeV states of N^{14}. Angular distributions of the $3.95\rightarrow 0$ and $3.95\rightarrow 2.31$ transitions were measured with a three-crystal pair spectrometer at a He^3 bombarding energy of 2.2 MeV. Analyses of these data determine solutions for x, the $E2/M1$ mixing ratio for the ground-state transition, of $x=-(0.37\pm0.04)$ or $x=-(2.80\pm0.27)$, where the phase convention is that of Litherland and Ferguson. Branching ratios of $(3.7\pm0.3)\%$ and $(96.3\pm0.3)\%$ were determined for transitions from the 3.95-MeV state to the ground state and to the 2.31-MeV first excited state, respectively. Combining these results with the previously determined $E2$ radiative width of the $3.95\rightarrow 0$ transition, it is seen that the smaller (in magnitude) solution for x corresponds to an inordinately large $M1$ strength for both the $3.95\rightarrow 0$ $\Delta T=0$ and $3.95\rightarrow 2.31$ $\Delta T=1$ transitions. For the larger value, $x=-(2.80\pm0.27)$, the radiative widths are $\Gamma_\gamma(M1)=0.140\pm0.013$ eV for the $3.95\rightarrow 2.31$ transition and $\Gamma_\gamma(M1)=(5.8\pm1.2)\times10^{-4}$ eV for the $3.95\rightarrow 0$ transition. Gamma-ray coincidence studies employing NaI(Tl) spectroscopy were also carried out at a He^3 bombarding energy of 6.0 MeV to determine the gamma branching of the N^{14} 7.03-MeV level to known lower lying levels. Branchings of $(0.5\pm0.1)\%$ and $(0.9\pm0.25)\%$ were determined for transitions to the first and second excited states of N^{14}, respectively, while upper limits of 0.4% (or less) were placed on possible transitions to the other excited states. Combining this with previous work gives an $E2$ radiative width for the $7.03\rightarrow 2.31$ $\Delta T=1$ transition of $(6\pm1.4)\times10^{-4}$ eV, and a total radiative width for the $7.03\rightarrow 3.95$ $\Delta T=0$ transition of $(11\pm3)\times10^{-4}$ eV.

I. INTRODUCTION

THE N^{14} ground state, 2.31-, 3.95-, and 7.03-MeV levels belong predominantly to the s^4p^{10} configuration.[1–3] These levels have $(J^\pi,T)=(1^+,0)$, $(0^+,1)$, $(1^+,0)$, and $(2^+,0)$, respectively, and are the only known or expected N^{14} s^4p^{10} states bound against nucleon emission. The static and dynamic properties of these states have been a subject of considerable theoretical interest over the years.[1,4–9] The primary reason for this is the difficulty of explaining the extremely long lifetime of C^{14} which decays by beta emission to the N^{14} ground state. The cancellation which must actually occur between the various contributions to the beta-decay matrix element cannot be achieved without either departing from the nucleon-nucleon interaction conventionally used in the lighter nuclei or by invoking configuration mixing in an arbitrary manner. Conversely, it should be possible to investigate the effective nucleon-nucleon interaction and/or the question of configuration mixing in the $1p$ shell by studies of the properties of the mass-14 s^4p^{10} states. Of course, it may be possible that these two questions are hopelessly entwined, and this too should be investigated.

Most of the measurable properties of the s^4p^{10} states are relatively insensitive to the changes in the wave functions necessary to reproduce the C^{14} beta-decay matrix element. However, some of the electromagnetic transitions connecting these states are quite sensitive to the wave functions of the states involved. Thus, any attempt to explain the C^{14} lifetime can be tested by reference to these electromagnetic transitions. For this reason, accurate and complete measurements of these transition rates and $E2/M1$ mixing ratios are clearly desirable.

In this paper we report on a measurement of the $E2/M1$ mixing ratio of the N^{14} $3.95\rightarrow 0$ transition (Sec. II) and a study (Sec. III) designed to search for weak cascades from the 7.03-MeV level to lower states of N^{14}, the main decay of this state being to the N^{14} ground state.[3]

II. THE N^{14} $3.95\rightarrow 0$ TRANSITION

A. Experimental Procedure

The N^{14} 3.95-MeV level decays 96% to the N^{14} 2.31-MeV level and only 4% to the ground state.[10–12] Thus the principle difficulty in studying the $3.95\rightarrow 0$ transition is that of differentiating the gamma rays from this transition from background events. Previous studies[11,12] of the $E2/M1$ mixing ratio of this transition used proton-gamma coincidence measurements in a collinear geometry (proton counter at 0° or 180° to the beam) following formation of the 3.95-MeV level by the $C^{12}(He^3,p)N^{14}$ reaction. This method differentiated against unwanted background events and produced alignment of the 3.95-MeV level. The alignment was

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determined by the angular distribution of the $3.95 \rightarrow 2.31$ transition, and the $E2/M1$ mixing ratio of the $3.95 \rightarrow 0$ transition was extracted from its angular distribution.

The use of particle-gamma coincidences to choose gamma rays associated with reaction particles traveling along the beam axis usually enhances the alignment above that which would be found for gamma rays associated with all reaction particles (i.e., intermediate particle unobserved). However, this is not necessarily so and even if so the advantage of performing singles measurements (i.e., higher counting rate) can outweigh the disadvantage of the loss of the degree of alignment.

In the present experiment the $C^{12}(He^3,p)N^{14}$ reaction was used to populate the 3.95-MeV level. The reaction protons were unobserved and a three-crystal pair spectrometer was used to detect the gamma rays. There are two major advantages in using a three-crystal pair spectrometer instead of a single NaI(Tl) detector: (1) Each gamma ray gives rise to a single line in the pair spectrum, of a shape which is quite accurately known. Thus the extraction of angular-distribution information is more readily and accurately accomplished in those cases where the gamma-decay spectrum is complex. (2) Unlike a single-crystal NaI(Tl) detector the efficiency for detection of a 3.95-MeV gamma ray is much enhanced over that for a 1.64-MeV gamma ray. For instance, for the three-crystal spectrometer we used, $\epsilon_p(3.95)/\epsilon_p(1.64)=7.95$, where $\epsilon_p(E)$ is the (two-escape peak) efficiency of detection for a gamma ray of energy E MeV. For a single 3×3-in. NaI(Tl) crystal, the corresponding ratio is $\epsilon_p'(3.95)/\epsilon_p'(1.64)=0.424$, where ϵ_p' is the photopeak efficiency. Thus the relative sensitivity for detection of a 3.95-MeV gamma ray compared to a 1.64-MeV gamma ray is for the three-crystal spectrometer enhanced by a factor of 18.9 over that for a single-crystal spectrometer. This has two effects—it is easier to obtain an accurate angular distribution for the 3.95-MeV gamma ray (more counting rate relative to background) and the effect of "summing" of the 1.64- and 2.31-MeV gamma rays becomes negligible (0.7% of the peak at 3.95 MeV in the pair spectrum was calculated to be the result of summing). In contrast, summing effects were an important source of error in the previous measurements.[11,12] That the present measurement of the $E2/M1$ mixing ratio of the $3.95 \rightarrow 0$ transition is considerably more accurate than the two previous measurements[11,12] results primarily from the advantages of the method as outlined above.

A bombarding energy $E_{He^3}=2.2$ MeV was used for these angular-distribution measurements. The carbon target, approximately 50-μg/cm^2 thick, was deposited on a 0.005-in. tantalum backing placed at 45° with respect to the incident beam. The tantalum was cooled by spraying an atomized jet of water onto it from behind. It was thus possible to run at a beam current of 10 μA, which was necessary in order to obtain the

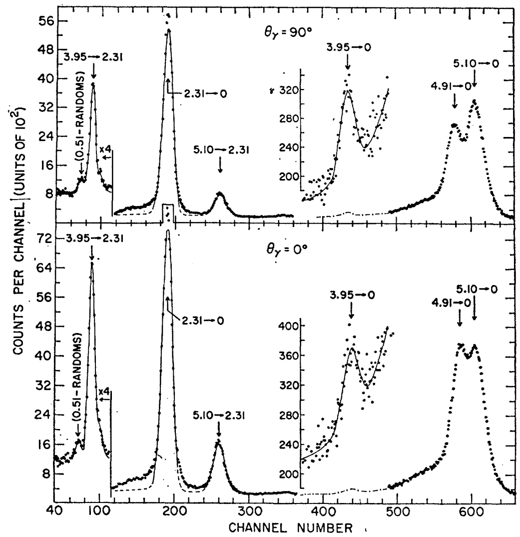

FIG. 1. Spectrum of gamma rays from the $C^{12}(He^3,p\gamma)N^{14}$ reaction measured with a three-crystal pair spectrometer at a bombarding energy of 2.2 MeV. These data, corresponding as indicated to detection angles $\theta_\gamma=0°$ and $\theta_\gamma=90°$, were obtained as part of the angular-distribution measurements described in the text. The smooth curves show the results of a computer fit to these data to determine, as a function of angle, the intensities of the $3.95 \rightarrow 2.31$ and $3.95 \rightarrow 0$ transitions relative to the $2.31 \rightarrow 0$ (isotropic) transition. Portions of these curves are dashed, to show that the indicated regions were excluded from the least-squares analysis. In the region of the $3.95 \rightarrow 0$ transition the plot has been expanded to show the results of the fitting procedure more clearly.

required statistical accuracy for the angular distribution of the N^{14} $3.95 \rightarrow 0$ transition. The front face of the center crystal of the spectrometer, which has been previously described,[13] was 10 cm from the target with a 2.5-cm diam lead collimator in front. A total of 12 runs was made mostly alternately at 0° and 90°. These varied in length from about 1 to 9 h. The three-crystal spectra obtained in two typical runs at 0° and 90° with respect to the beam are given in Fig. 1. The 1.64- and 2.31-MeV peaks are clearly visible. While by no means as intense as these peaks, the 3.95-MeV peak stands out from the background and has a peak intensity at least equal to that of the background. The region containing the 1.64- and 2.31-MeV peaks and that containing the 3.95-MeV peak were fitted separately by a Gaussian least-squares fitting program.[13,14] In this fitting, the well-known spectral response of the spectrometer enabled the area of the 3.95-MeV peak to be accurately extracted in spite of the rather low peak-to-background ratio. Since the angular distribution of the 2.31-MeV gamma ray is isotropic, its yield was used to normalize the yields of the 1.64- and 3.95-MeV gamma rays at each angle.

The asymmetry on the high side of the 1.64-MeV

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peak and the poor fit to the tails of the 2.31-MeV peak in Fig. 1 are effects associated with the very high singles counting rates used in this experiment. These effects were investigated by varying the beam intensity and the peak-fitting procedures. The changes in the peak intensities due to these effects were found to be small and could be estimated with sufficient accuracy so that the net uncertainty due to them was not unduly important. This uncertainty was incorporated in the final results.

There was a buildup of 20% in the target thickness during the experiment. It was determined that there are no resonances near the bombarding energy used and that $W(90°)/W(0°)$ for the 1.64-MeV angular distribution near $E_{He^3}=2.2$ MeV was constant or at most slowly varying. Thus, the carbon buildup should not affect the result. To check on this the anisotropies determined from consecutive 0° and 90° points were compared as a function of time, and with the final averaged value. No dependence on time was observed. A least-squares fit to the Legendre polynomial expansion $A_0[1+a_2P_2(\cos\theta)]$ gave the following values for a_2: for the 1.64-MeV transition, $a_2(10)=0.190\pm0.004$, while for the 3.95-MeV transition, $a_2(11)=-0.279\pm0.015$, where the error on $a_2(11)$ has been increased to take account of the possible presence of a 3.90-MeV gamma ray from the 6.21-MeV level, as discussed below.

The 6.21-MeV level of N^{14} is known to decay $(76\pm3)\%$ by a 3.90-MeV gamma ray to the 2.31-MeV level and $(24\pm3)\%$ to the ground state.[13] Since the pair spectrometer was incapable of distinguishing 3.90- and 3.95-MeV gamma rays, it was essential to the above considerations that the 6.21-MeV level should have been only weakly excited. The angular distribution had been done at the lowest possible beam energy consistent with a sufficient feeding of the 3.95-MeV level, $E_{He^3}=2.2$ MeV, which was only 280 keV above threshold for formation of the 6.21-MeV level. One would not expect to obtain a significant population of the 6.21-MeV level this close to its threshold, and would therefore expect that the intensity of the $6.21\rightarrow2.31$ transition would be sufficiently weak, relative to the $3.95\rightarrow0$ transition, that it could be neglected. However, since the resolution of the three-crystal pair spectrometer was not capable of resolving 3.95- and 3.90-MeV gamma rays, the only way to determine the relative intensity of the $6.21\rightarrow2.31$ transition would have been from the intensity of the alternate $6.21\rightarrow0$ branch. Unfortunately, because of the presence in the three-crystal pair spectrum of the O^{15} $6.18\rightarrow0$ and N^{15} $6.32\rightarrow0$ transitions, this method was not sufficiently sensitive. These latter gamma rays originated from the $C^{13}(He^3,n)O^{15}$ and $C^{13}(He^3,p)N^{15}$ reactions because of the 1% C^{13} in the natural-carbon target.

Consequently, it was necessary to perform a subsidiary γ-γ coincidence experiment in order to place a strict upper limit on possible contributions to the 3.95-MeV peak due to 3.90-MeV gamma rays from the 6.21-MeV level. This measurement was also carried out at $E_{He^3}=2.2$ MeV, and a TMC 16 384-channel analyzer was used to measure the coincidence spectrum of gamma rays observed with two 3×3-in. NaI(Tl) detectors. From the spectrum thus measured in coincidence with 2.31-MeV gamma rays, an upper limit on the relative intensities of 3.90- and 1.64-MeV gamma rays, signifying de-excitation of the 6.21- and 3.95-MeV levels, respectively, was readily determined. This information was then used to compute, from the intensity of the $3.95\rightarrow2.31$ transition as observed in the three-crystal pair data, an upper limit on the intensity of a possible 3.90-MeV component in the 3.95-MeV peak. As a check on this method, the coincidence experiment was repeated at a bombarding energy $E_{He^3}=3.1$ MeV, where the 6.21-MeV level was strongly formed. In this instance, the relative intensities of the 1.64- and 3.90-MeV gamma rays (and also the 6.21-MeV gamma ray) could be determined directly from the singles spectrum and thus a necessary and satisfactory check on the coincidence measurements was obtained. In summary, then, we determined that the limit on the intensity ratio of 3.90- and 3.95-MeV gamma rays is, with a confidence of 95%, $I_\gamma(3.90)/I_\gamma(3.95)\leqslant0.035$ for $E_{He^3}=2.2$ MeV. The uncertainty in the angular distribution of the $3.95\rightarrow0$ transition due to this possible 3.5% impurity had the effect of increasing the error on the angular-distribution coefficient a_2 by a factor of approximately 2 over the purely statistical error. We have estimated that all other sources of error were negligible compared with this.

B. Results

The angular distributions which were obtained for the $3.95\rightarrow2.31$ and $3.95\rightarrow0$ transitions are shown in Fig. 2. The lines drawn through the points are the best-fitting curves obtained for a simultaneous fitting of the angular distributions as a function of the population parameters of the 3.95-MeV level and the mixing ratio of the $3.95\rightarrow0$ transition as discussed below. Since the spins involved are $J(3.95)=1$, $J(2.31)=0$, and $J(0)=1$, the value of the mixing ratio (x) can easily be obtained, since[13,15]

$$\frac{-2a_2(11)}{a_2(10)}=\frac{-2\rho_2(1)F_k(11)Q_2}{\rho_2(1)F_k(10)Q_2}=f(x)\equiv\frac{1-6x+x^2}{1+x^2}, \quad (1)$$

where $\rho_2(1)$, the statistical tensor describing the alignment of the state, and Q_2, the attenuation coefficient of the angular distribution due to the finite size of the center crystal, cancel out. (Actually Q_2 is somewhat dependent on gamma-ray energy. However, because of the small solid angle subtended by the three-crystal

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

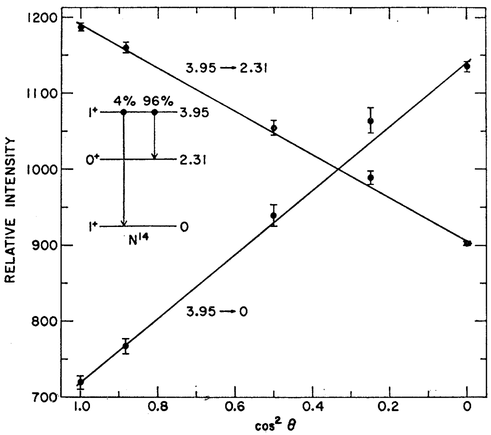

FIG. 2. Angular distributions of the primary gamma rays from the N^{14} 3.95-MeV level populated in the $C^{12}(He^3,p)N^{14}$ reaction at $E_{He^3}=2.2$ MeV. Each data point represents the average of two or more measurements as obtained with the three-crystal pair spectrometer. The curves shown are the result of an even-order Legendre-polynomial fit to the experimental data.

spectrometer, Q_2 differed practically negligibly from unity and so neglecting the slight energy dependence introduced negligible error.) $F_k(ab)$ is defined by Poletti and Warburton.[15] The phase convention of Litherland and Ferguson[16] has been used. The solution of the above equation is illustrated in Fig. 3. To one standard deviation there are two allowed regions, $x=-0.37\pm0.04$ and -2.80 ± 0.27, while to two standard deviations the corresponding values are $x=-0.37\pm0.08$ and -2.80 ± 0.50. The region $-2.30<x<-0.56$ is thus eliminated with greater than 95% probability.

The efficiency of the three-crystal spectrometer has been well established and a branching ratio could be extracted for the 3.95-MeV level. The result is that this level decays $(3.7\pm0.3)\%$ to the ground state of N^{14} and $(96.3\pm0.3)\%$ to the 2.31-MeV state of N^{14}. The results obtained in the present work for the mixing ratio and branching ratio are compared with previous determinations in Tables I and II. We adopt the weighted averages given in these tables.

The $E2$ radiative width of the $3.95\to0$ transition has been determined from inelastic electron-scattering measurements[2] to be $(4.81\pm0.33)\times10^{-3}$ eV. This result,

TABLE I. The mixing ratio for the $3.95\to0$ transition in N^{14}. The phase convention of Refs. 15 and 16 is used.

$x(E2/M1)$ Low value	High value	$f(x)$[a]	Reference
-0.35 ± 0.15	$-5\leq x\leq-2$	2.80 ± 0.60	11
-0.32 ± 0.13	$-5.2\leq x\leq-2.2$	2.70 ± 0.60	12
-0.37 ± 0.04	-2.80 ± 0.27	2.94 ± 0.17	Present work
-0.35 ± 0.04	-2.87 ± 0.27	2.87 ± 0.16	Weighted average

[a] Equation (1) of the text.

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

TABLE II. The branching ratio of the 3.95-MeV level in N^{14}. The percentage branch to the ground state of N^{14} is given.

Branching (%)	Reference
$3.7\ \pm0.6$	10
$3.8\ \pm0.5$	11
$3.6\ \pm0.6$	12
$3.7\ \pm0.3$	Present work
3.70 ± 0.20	Weighted average

together with the branching ratio for the $3.95\to0$ transition, determines the $M1$ strengths of the $3.95\to0$ and $3.95\to2.31$ transitions for a given value of the $E2/M1$ mixing ratio in the former transition. The dependence on this mixing ratio of the $3.95\to0$ and $3.95\to2.31$ $M1$ transition strengths is shown in Fig. 4. The $M1$ transition strengths are in Weisskopf units (Wu), i.e., $\Gamma_\gamma(M1)=0.021E_\gamma^3|M(M1)|^2$ eV, with E_γ in MeV, and are given by

$$|M(M1)|^2{}_{3.95\to0}=(3.72\times10^{-3})/x^2 \qquad (2)$$

and

$$|M(M1)|^2{}_{3.95\to2.31}=1.35(1+x^2)/x^2 \qquad (3)$$

which results from $\Gamma_\gamma(E2)=4.81\times10^{-3}$ eV and a branching of 3.7% for the $3.95\to0$ transition. The two alternate experimental values of $x(E2/M1)$ from Table I are shown in Fig. 4.

Figure 4 is designed to show that the larger of these

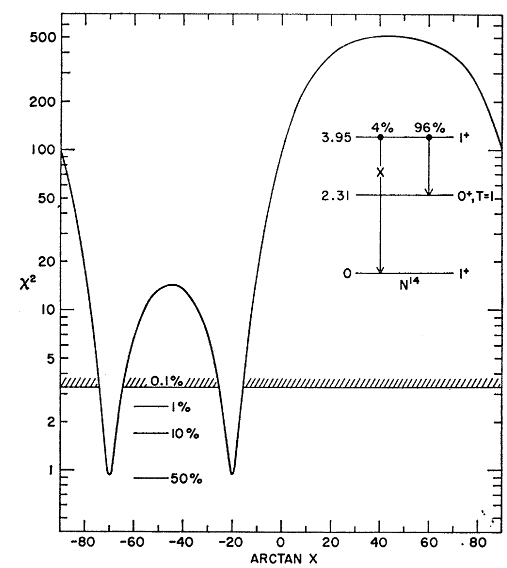

FIG. 3. Plot of χ^2 versus arctan x for a simultaneous fit to the angular-distribution data on the N^{14} 3.95-MeV level. As indicated in the insert, x refers to the $E2/M1$ mixing ratio in the $3.95\to0$ ground-state transition. The $3.95\to2.31$ transition is fixed as $M1$ in character by the known spins and parities of these two levels. The probability that χ^2 exceeds the value marked as the 0.1% limit is 0.1%; various other limits are also indicated. Solutions for x, corresponding to the minima in χ^2, are thus found as $x=-(0.37\pm0.04)$ and $x=-(2.80\pm0.27)$. The region $-2.30<x<-0.56$ is eliminated from consideration with greater than 95% probability.

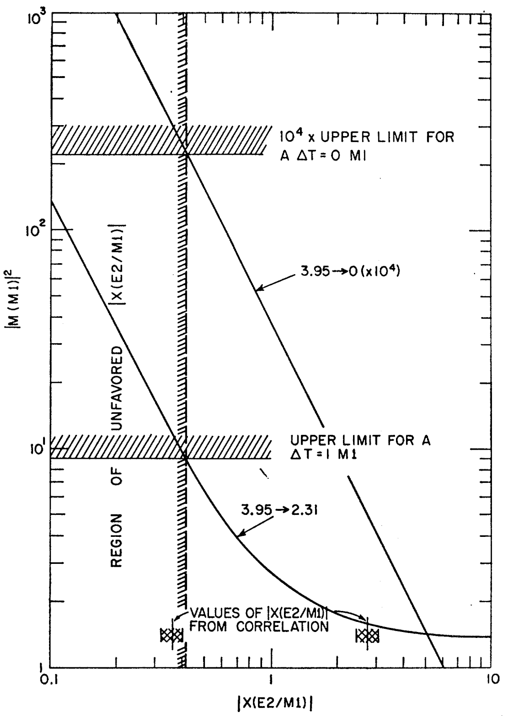

FIG. 4. A comparison of $M1$ strengths observed in the systematics of light nuclei ($Z \leq 10$) with those observed in the gamma deexcitation of the N[14] 3.95-MeV level. The solid curves show the $M1$ strengths $|M(M1)|^2$ (in Weisskopf units) computed for the $3.95 \to 0$ and $3.95 \to 2.31$ transitions as a function of $|x(E2/M1)|$, the mixing amplitude in the $3.95 \to 0$ transition. These computations are based on experimentally determined values for the $E2$ radiative width of the $3.95 \to 0$ transition and the gamma branching ratios for the 3.95-MeV level. Upper limits on $|M(M1)|^2$ suggested from the systematics of light nuclei, as explained in the text, are indicated by the cross-hatched horizontal lines. [We note that the curves shown for the $3.95 \to 0$ transition and for the corresponding upper limit on $|M(M1)|^2$ have been multiplied by a factor 10^4, as indicated.] For $\Delta T=0$, $M1$ transitions ($3.95 \to 0$) an upper limit of 0.021 Wu is suggested corresponding to a restriction $|x(E2/M1)|>0.41$. For $\Delta T=1$, $M1$ transitions ($3.95 \to 2.31$) the suggested upper limit of 9 Wu corresponds to a restriction on x of $|x(E2/M1)|>0.41$. (That these restrictions on x are identical is only coincidence.) Hence we conclude that values $|x(E2/M1)|<0.41$ are extremely unlikely, as indicated by the cross-hatched vertical line designating the region of unfavored $|x(E2/M1)|$. The two solutions for $|x(E2/M1)|$ determined in the present correlation experiment are indicated. From this we conclude that only the larger value, $x(E2/M1)=-(2.87\pm0.27)$, should be accepted.

two values of $x(E2/M1)$ is quite probably the correct one since the smaller value results in unrealistically large $M1$ strengths for both the $3.95 \to 0$ and $3.95 \to 2.31$ transitions. This conclusion is based on systematics of $\Delta T=0$ and $\Delta T=1$ rates for $M1$ transitions in self-conjugate nuclei. A recent compilation[17] of such rates has been made for $Z \leqslant 10$. Of the 18 $\Delta T=0$ and 34 $\Delta T=1$ transitions in this compilation no $\Delta T=0$ transitions have strengths greater than 0.021 Wu and no $\Delta T=1$ transitions have strengths greater than 9 Wu. In addition only two $\Delta T=1$ transitions are known with $M1$ strengths greater than 4 Wu and these are both $0^+ \to 1^+$ transitions which have strengths intrinsically stronger by a factor of 3 than $1^+ \to 0^+$ transitions such as is the N[14] $3.95 \to 2.31$ transition under consideration. From these empirical data, we conclude that it is extremely unlikely that a $\Delta T=1$, $M1$ transition in N[14] (e.g., $3.95 \to 2.31$) has a strength greater than 9 Wu or that a $\Delta T=0$, $M1$ transition in the same nucleus (e.g., $3.95 \to 0$) has a strength greater than 0.021 Wu. This conclusion is illustrated in Fig. 4 by the horizontal lines (with cross hatching) at the appropriate values of $|M(M1)|^2$. It is coincidental that these two lines cross the corresponding curves of $|M(M1)|^2$ versus $|x(E2/M1)|$ at the same value of $|x(E2/M1)|$. Both upper limits on $|M(M1)|^2$ correspond to lower limits on $|x(E2/M1)|$ of 0.41 so that the lower value of $|x(E2/M1)$, 0.35 ± 0.04, is unfavored. We therefore shall accept the upper value of $x(E2/M1)$, $-(2.87\pm0.27)$, as the correct one, although we note that the exclusion of the lower value is not rigorous.

In summary, the results given in Tables I and II together with the inelastic electron-scattering results of Bishop *et al.*[2] lead to the following radiative widths for the decay of the N[14] 3.95-MeV level:

$$\Gamma_\gamma(M1)=0.140\pm0.013 \text{ eV}$$

for the $3.95 \to 2.31$ transition, and

$$\Gamma_\gamma(M1)=(5.8\pm1.2)\times10^{-4} \text{ eV}$$

and

$$\Gamma_\gamma(E2)=(4.81\pm0.33)\times10^{-3} \text{ eV}$$

for the $3.95 \to 0$ transition, with the $E2$ and $M1$ matrix elements being of opposite phase.

III. THE DECAY OF THE N[14] 7.03-MeV LEVEL

The N[14] 7.03-MeV level decays predominantly to the ground state. Limits of 2 and 1%, respectively, have been set on the branch to the 3.95-MeV level.[12,18] The decay to the 2.31-MeV level has been reported[3,12,18] as less than 5, 4, and 1%, respectively.

The radiative width of the N[14] 7.03-MeV level has been investigated by means of the resonance-fluorescence technique.[3] The result can be expressed in eV as $\Gamma_\gamma(7.03 \to 0)=(0.122\pm0.012)/\text{RB}$ where RB is the relative branching of the 7.03-MeV level to the ground state expressed as a fraction of the total decays. Thus a search for cascade transitions from the 7.03-MeV level, as well as being of interest in its own right, is important in order to eliminate the uncertainty in the above value of $\Gamma_\gamma(7.03 \to 0)$ due to that in RB. The present experiment was designed primarily to measure branching ratios for the $7.03 \to 3.95$ and $7.03 \to 2.31$ transitions but also to search for transitions to the N[14] states between 4.9 and 6.5 MeV.

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

[18] F. C. Young (private communication).

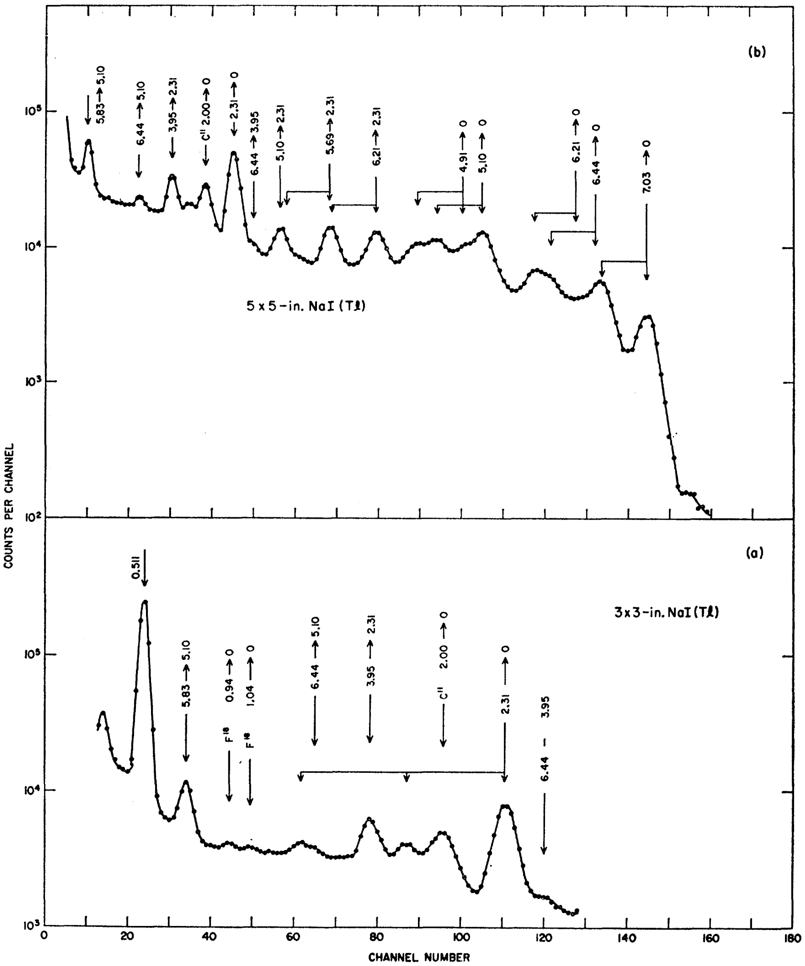

FIG. 5. Spectra of gamma rays from the $C^{12}(He^3,p\gamma)N^{14}$ reaction measured with NaI(Tl) detectors at a He^3 bombarding energy of 6.0 MeV. Curves (a) and (b) show the spectra measured, respectively, by the 3×3-in. and 5×5-in. detectors under the conditions which applied for the two-parameter measurements described in the text. Transitions in N^{14} are identified by the excitation energies (in MeV) of the initial and final levels between which the transition occurs. Contaminant peaks from F^{18} and C^{11} are also identified. The expected positions of various escape peaks are also indicated.

Two gamma-ray coincidence experiments were performed to search for cascade transitions from the 7.03-MeV level, both using the $C^{12}(He^3,p)N^{14}$ reaction to populate the 7.03-MeV level at a He^3 bombarding energy of 6.0 MeV. In the first measurement, two NaI(Tl) detectors were utilized in a two-parameter analysis. In the second measurement, three NaI(Tl) detectors were utilized in a triple-coincidence experiment designed, in particular, to investigate transitions to the 3.95-MeV level.

A. Gamma-Ray Double-Coincidence Measurements

The two NaI(Tl) detectors were placed ~2.5 cm from the target site both at 90° to the beam and on opposite sides of the target. Both detectors—one 3×3 in. and one 5×5 in.—were shielded by 5 cm or more of lead against the general room background. Coincidence pulses from the two detectors were analyzed by a TMC 16 384-channel analyzer operating in a 128×128-channel mode. The coincidence resolving time was ~30 nsec. The target for these measurements was a foil of natural carbon (~100 keV thick to the He^3 beam) mounted on a tantalum backing. The singles spectra shown in Fig. 5 illustrate that the feeding of the 7.03-MeV level was sufficient for our purposes. These data were acquired at a beam current of 0.0003 μA under conditions similar to those employed for the two-parameter run.

The lower plot shows the spectrum for $0.3 \leqslant E_\gamma \leqslant 2.6$ MeV as viewed by the 3×3-in. detector. The upper plot shows the spectrum of gamma pulses measured by the 5×5-in. detector. In addition to the expected peaks from N^{14} transitions, we also see the $2.00 \rightarrow 0$ transition from C^{11} formed in the $C^{12}(He^3,\alpha)C^{11}$ reaction and peaks at 0.94 and 1.04 MeV which we ascribe to the $O^{16}(He^3,p)F^{18}$ reaction, probably resulting from an oxide present in the target or backing.

The populations of lower lying states relative to the 7.03-MeV level of interest were obtained from the data of Fig. 5(b) by standard "spectrum-stripping" procedures. From the known branching ratios and from detector efficiency curves, the population of other states relative to the 7.03-MeV level are as indicated:

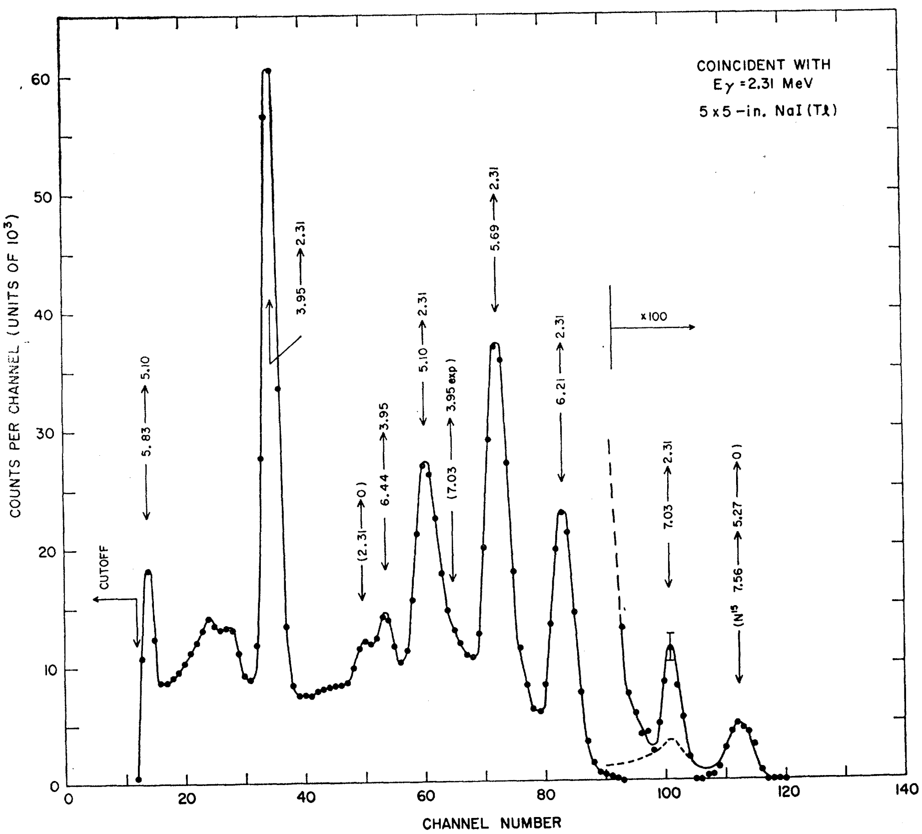

FIG. 6. Partial results of a two-parameter analysis of γ-γ coincidences in the $C^{12}(He^3,p\gamma)N^{14}$ reaction at $E_{He^3}=6.0$ MeV. This plot shows the spectrum measured by the 5×5-in. detector in coincidence with 2.31-MeV gamma rays viewed by the 3×3-in. detector. The various lines are identified according to the excitation energies (in MeV) of the initial and final states between which the transition occurs. In addition to expected transitions from lower lying states of N^{14}, we see a peak at $E_\gamma=4.72$ MeV which we identify with the $7.03\rightarrow2.31$ transition. The peak at 5.27 MeV is assigned to the $C^{13}(He^3,p)N^{15}$ reaction because of the 1% abundant C^{13} isotope present in the natural-carbon target. It is evident that a weak $7.03\rightarrow3.95$ transition would be masked by the presence of other stronger transitions.

3.95(1.02), 4.91(0.77), 5.10(2.20), 5.69(1.27), 5.83(0.52), 6.21(1.50), and 6.44(0.67), when by definition the 7.03-MeV level has a relative population of 1.00. The values indicated incorporated information obtained from the two-parameter measurements, which were found to agree well with the independent singles measurements. We assign an over-all uncertainty of ~20% to the relative populations.

For the γ-γ coincidence measurements, the two-parameter analyzer was operated such that it analyzed coincidence pulses from the two detectors falling in the region below channel number 128 in each of the two plots of Fig. 5. Data were acquired in a run of ~21 h at a beam current of 0.0003 μA for a total integrated charge of 21 μC. At this low current, the ratio of randoms to reals (integrated over the whole spectrum) was determined to be 0.025.

The general procedures of the computer-implemented data analysis have been described previously.[19] Figure 6 shows the spectrum of gamma rays measured by the 5×5-in. detector in coincidence with the 2.31-MeV photopeak viewed by the 3×3-in. detector. A background spectrum due to coincidences with the "Compton tails" of higher lying gamma rays [see Fig. 5(a)] has been subtracted as have also the accidentals. That this procedure is effective is evident from the small amount of 2.31-MeV peak remaining in the spectrum of Fig. 6 as compared to Fig. 5(a).

Referring to Fig. 6 we see, as expected, transitions leading to the 2.31-MeV level from the 6.44-, 6.21-, 5.83-, 5.69-, 5.10-, and 3.95-MeV levels. The intensities of these transitions were used to confirm the relative feeding of these states as described above. Additionally, we see peaks of energy 5.27 and 4.72 MeV. The former we ascribe to the N^{15} $7.56\rightarrow5.27\rightarrow0$ cascade resulting from the $C^{13}(He^3,p)N^{15}$ reaction because of the 1% abundant C^{13} isotope present in the natural carbon target. (That the energy of the gamma ray coincident with the 5.27-MeV peak is different from the N^{14} $2.31\rightarrow0$ transition was ascertained from the two-parameter spectrum, in agreement with this assignment.) The shape of the 5.27-MeV spectrum underlying the 4.72-MeV peak is indicated by the dashed curve.

The energy of the 4.72-MeV peak matches (within the experimental uncertainty of ~20 keV) that expected for a $7.03\rightarrow2.31$ transition. From its intensity relative to the stronger lower energy peaks, and from the relative state populations listed above, we compute the intensity of the $7.03\rightarrow2.31$ transition as (0.5 ± 0.1)% relative to the ground-state transition.

We further note that since the 4.72-MeV peak is

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

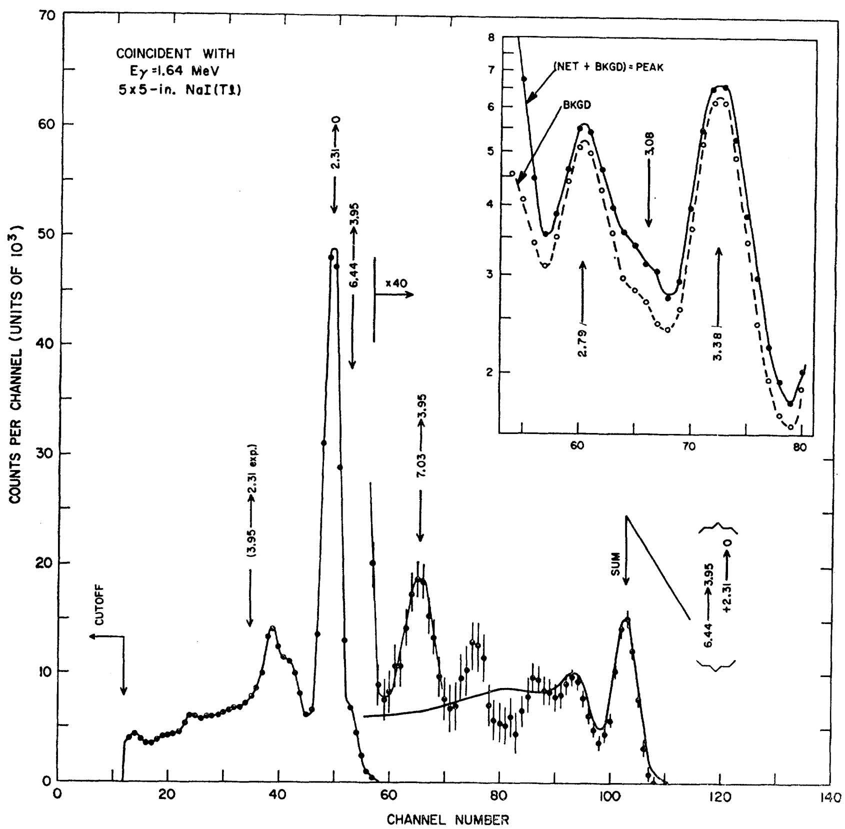

FIG. 7. Partial results of a two-parameter analysis of γ-γ coincidences in the $C^{12}(He^3,p\gamma)N^{14}$ reaction at $E_{He^3}=6.0$ MeV. The main plot shows the spectrum measured with the 5×5-in. detector in coincidence with 1.64-MeV gamma rays viewed by the 3×3-in. detector. In addition to the peaks at 2.49 and 2.31 MeV resulting from de-excitation of the 6.44- and 3.95-MeV levels, we see a peak at 3.08 MeV which is assigned to a $7.03\rightarrow 3.95$ transition. The peak at 4.80 MeV results from summing in the 5×5-in. detector of 2.31- and 2.49-MeV gamma rays resulting from the $6.44\rightarrow 3.95\rightarrow 2.31\rightarrow 0$ cascade. The computed shape and intensity of this peak is indicated. These data were obtained as the difference between (a) the spectra coincident with the 1.64-MeV photopeak and (b) the background spectra resulting from coincidence with "tails" underlying the 1.64 MeV photopeak. These spectra are shown in the insert; the presence of a peak at ∼3.08 MeV is directly apparent from these data.

observed in coincidence with a 2.31-MeV photopeak, the transition must originate from a level of excitation energy $E_{ex}\gtrsim(4.72+2.31=7.03)$ MeV. Of the known or probable contaminants only N^{15} or O^{15} have bound levels satisfying this limitation, and neither can give rise to a 4.72-MeV peak. Hence, we assign the transition to N^{14} $7.03\rightarrow 2.31$ with no further reservations.

Figure 7 shows the spectrum of gamma rays recorded by the 5×5-in. detector in coincidence with the 1.64-MeV photopeak viewed by the 3×3-in. detector. The main plot shows the net spectrum after removal of the "background" spectrum coincident with the continuum lying under the 1.64-MeV photopeak [see Fig. 5(a)]. The principal background component arises from coincidences with pulses in the Compton distribution of the 2.31-MeV gamma ray. Since the shape of the 2.31-MeV pulse-height distribution had been determined accurately from the spectra observed in coincidence with the 2.79- and 3.38-MeV gamma rays present in the same data matrix, its presence could be accounted for by careful normalizing of the background spectrum before subtraction.

Referring to Fig. 7, we observe cascade transitions from the 6.44- and 3.95-MeV levels of N^{14} in coincidence with 1.64-MeV gamma rays. The peak at 4.80 MeV is clearly due to summing of the 2.31- and 2.49-MeV gamma rays from the $6.44\rightarrow 3.95\rightarrow 2.31\rightarrow 0$ cascade. The peak width is narrower than would be expected for a single transition of this energy, and the peak intensity agrees well with the expected sum peak computed from the observed intensity of the $6.44\rightarrow 3.95$ transition. The solid curve of Fig. 7 shows the shape of the sum peak computed for summing of 2.31- and 2.49-MeV gamma rays. It is evident that this summing accounts for most of the intensity above channel 60, with the exception of the peak at 3.08 MeV which can now be assigned to the $7.03\rightarrow 3.95$ cascade transition. The presence of a 3.08-MeV transition is evident also from the spectra shown in the insert. The origin of the "apparent structure" in the region of channels 72–85 is uncertain, but could possibly arise from a very small gain shift resulting from the different counting rates obtained for the two spectra shown in the insert, although the mechanism for such a gain shift is not suggested by the electronics of the two-parameter analyzer. We note, however, that in contrast to the steep slopes of the 3.38- and 2.79-MeV peaks, the 3.08-MeV gamma ray corresponds to a region of pulse height where the counting rate follows a more gradual trend; hence we do not feel that the appearance of a 3.08-MeV peak could possibly be generated by any such spurious effects.

In conclusion, we assign the 3.08-MeV transition to a $7.03\rightarrow 3.95$ cascade, and compute an intensity for

TABLE III. Summary of present determination of branching ratios for transitions from the N^{14} 7.03-MeV state. For convenience the branching of the intermediate states as determined from this and other investigations is also summarized.

Transition	Branching ratio (%)	Branching of intermediate state Initial level	Final level	Branching[a] ratio (%)
$7.03\rightarrow 0$	98.6±0.3			
$7.03\rightarrow 2.31$	0.5±0.1	2.31	0	100
$7.03\rightarrow 3.95$	0.9±0.25	3.95[b]	0	3.7±0.2
			2.31	96.3±0.2
$7.03\rightarrow 4.91$	<0.3	4.91[b,c]	0	100
$7.03\rightarrow 5.10$	<0.4	5.10[d,e]	0	77±3
			2.31	23±3
$7.03\rightarrow 5.69$	<0.4	5.69[b,d,e]	0	38±3
			2.31	62±3
$7.03\rightarrow 5.83$	<0.4	5.83[e]	0	29±4
			5.10	71±4
$7.03\rightarrow 6.21$	<0.3	6.21[b,d,e]	0	23±3
			2.31	77±3
$7.03\rightarrow 6.44$	<0.3	6.44[b,e]	0	71±3
			3.95	20±2
			5.10	9±2

[a] Branching ratios quoted for the various states are averages of, or best values from, the results quoted in:
[b] Present report.
[c] E. K. Warburton *et al.*, Ref. 13.
[d] Fay Ajzenberg-Selove and C. Lauritsen [Nucl. Phys. 11, 1 (1959)].
[e] S. Gorodetzky *et al.*, Ref. 12.

this branch of (1.0±0.3)% relative to the $7.03\rightarrow 0$ transition.

Further examination of these two-parameter data revealed no evidence for transitions from the N^{14} 7.03-MeV level to those 6 remaining levels of $E_x \geqslant 4.91$ MeV. From the absence in the coincidence spectra of low-energy gamma rays leading from the 7.03-MeV level to the levels at 4.91, 5.10, 5.69, 6.21, and 6.44 MeV (as determined from the spectra in coincidence with the ground state transitions from these levels), upper limits of 0.3, 0.4, 0.4, 0.3, and 0.3% were placed on the intensities of possible transitions to these levels from the 7.03-MeV level. Similarly, an upper limit of 0.4% was deduced for a possible $7.03\rightarrow 5.83$ cascade from the absence of the expected 1.20-MeV gamma ray in coincidence with the 5.10-MeV gamma ray resulting from the subsequent $5.83\rightarrow 5.10$ cascade, which is known[12] to proceed with a branching ratio of (71±4)%.

These results are summarized in Table III. The value quoted for the $7.03\rightarrow 3.95$ transition incorporates the results, to be described in the next subsection, of the gamma-ray triple-coincidence measurement.

B. Gamma-Ray Triple-Coincidence Measurements

For these measurements three 3×3-in. NaI(Tl) detectors were placed at distances of about 3 cm from the target spot. Pulses from detectors (1) and (2) were analyzed by the two-parameter analyzer which was gated by an external coincidence circuit which imposed the following requirements: (a) that there was a fast (30-nsec) coincidence recorded between pulses from all three detectors, and (b) that these were in slow coincidence with a pulse from a voltage gate set on the 2.31-MeV photopeak seen by detector (3). The resultant two-parameter spectrum therefore displayed primarily pairs of coincident gamma rays resulting from multiple cascades leading to the 2.31-MeV first-excited state of N^{14}.

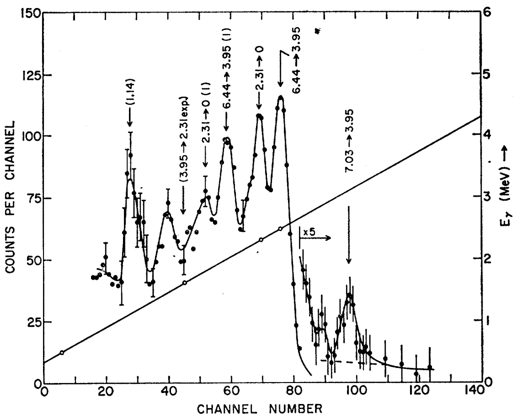

FIG. 8. Spectrum of gamma rays measured by a 3×3-in. NaI(Tl) detector in triple coincidence with 1.64- and 2.31-MeV gamma rays detected by two other detectors. In this spectrum we see both the 2.49- and 2.31-MeV gamma rays from the $6.44\rightarrow 3.95\rightarrow 2.31\rightarrow 0$ cascade, since the voltage gate set on the 2.31-MeV photopeak was broad enough to encompass most of the 2.49-MeV photopeak also. The peak at 3.08 MeV is ascribed to the first member of a $7.03\rightarrow 3.95\rightarrow 2.31\rightarrow 0$ cascade, and, from its intensity, a branching ratio of (0.8±0.3)% is computed for the $7.03\rightarrow 3.95$ transition. The origin of the 1.14-MeV peak is uncertain, but on the basis of its energy would correspond to a $5.10\rightarrow 3.95$ branch of 0.8% intensity. In order to improve the statistics of the individual data points, the raw data have been averaged over a width of two channels, since this procedure is consistent with the observed detector resolution. In the region above channel 104 we have plotted the average of four channels.

This procedure was used to search for weak transitions to the 3.95-MeV level, since it automatically removes from the two-parameter spectrum all gamma rays resulting from direct population of the 2.31-, 3.95-, 4.91-, 5.10-, 5.69-, and 6.21-MeV levels. Further, since the 3.95-MeV level decays predominantly (96%) by cascade to the 2.31-MeV level, an additional degree of sensitivity is gained.

A single measurement of 12-h duration was made at a beam energy of 6.0 MeV. In other respects, the measurement was identical to that described in the previous subsection, as were also the procedures of analysis.

Figure 8 presents a portion of the data from the resultant two-parameter spectrum, showing the spectrum of gamma rays from one detector in coincidence with the 1.64-MeV photopeak as viewed by the other. Since detectors (1) and (2) were identical, this spectrum was constructed as the sum of the two spectra of (1) and (2), each measured in coincidence with the 1.64-MeV photopeak seen by the other.

Figure 8 therefore shows the spectrum of gamma rays coincident with both 1.64-MeV gamma rays and also

2.31-MeV gamma rays. Thus we see the 2.49-MeV gamma resulting from the $6.44 \rightarrow 3.95$ cascade transition. Since the voltage gate on detector (3) also included the 2.49-MeV photopeak, we see a 2.31-MeV transition resulting from triple coincidences with 2.49- and 1.64-MeV gamma rays.

The presence of these two components resulting from the $6.44 \rightarrow 3.95 \rightarrow 2.31 \rightarrow 0$ cascade accounts for the four intense higher energy peaks of Fig. 8. We also observe a peak at 3.08 MeV which must be due to the $7.03 \rightarrow 3.95$ transition. From its area we compute an intensity for this transition of $0.8 \pm 0.3\%$ relative to the $7.03 \rightarrow 0$ transition. This is in excellent agreement with the result obtained from the γ-γ analysis of the previous subsection, and we therefore adopt the average value $(0.90 \pm 0.25)\%$ given in Table III.

Also evident in Fig. 8 are a weak peak at 1.5 MeV, of unknown origin, and a peak at 1.14 MeV, which would correspond to a possible $5.10 \rightarrow 3.95$ transition with a branching ratio of 0.8%. Since both peaks arise in a region of low pulse height where the background was markedly worse, their origin remains somewhat suspect.

In summary, then, it has been determined that the N^{14} 7.03-MeV level decays by gamma-ray emission to the ground state and to the first and second excited states with branchings of $(98.6 \pm 0.3)\%$, $(0.5 \pm 0.1)\%$, and $(0.9 \pm 0.25)\%$, respectively. The last two results are consistent with previous limits on these branches. The radiative width of the $7.03 \rightarrow 0$ transition, based on the resonance-fluorescence results of Swann,[3] is $(0.122 \pm 0.012)/(0.986) = (0.124 \pm 0.012)$ eV, where the contribution to the uncertainty of this measurement from possible branches to N^{14} states between 4 and 7 MeV is negligible. From the previously[20] determined mixing in the ground-state decay, $x(E2/M1) = +(0.6 \pm 0.1)$, we compute the partial widths for the $E2$ and $M1$ components of the $7.03 \rightarrow 0$ de-excitation as

$$\Gamma_\gamma(M1) = (0.091 \pm 0.013) \text{ eV},$$
$$\Gamma_\gamma(E2) = (0.033 \pm 0.009) \text{ eV}.$$

The latter value is in fair agreement with the result of (0.046 ± 0.003) eV from inelastic electron scattering.[2] The $E2$ radiative width for the $7.03 \rightarrow 2.31$ transition is

$$\Gamma_\gamma(E2) = (0.62 \pm 0.14) \times 10^{-3} \text{ eV}$$

and the *total* width for the $7.03 \rightarrow 3.95$ transition is

$$\Gamma_\gamma(M1,E2) = (1.12 \pm 0.33) \times 10^{-3} \text{ eV}.$$

IV. SUMMARY

Considerably more accurate values were obtained for the two alternate values of the $E2/M1$ mixing ratio of the N^{14} $3.95 \rightarrow 0$ transition and an argument was presented which strongly favors the value with the larger magnitude.

Transitions from the N^{14} 7.03-MeV level to the 2.31- and 3.95-MeV levels were sought for and found and rather stringent limits were placed on possible transitions to higher levels of N^{14}. The $7.03 \rightarrow 2.31$ transition is rather interesting in that it is a $\Delta T = 1$ $E2$ transition. The only other well-authenticated $\Delta T = 1$ $E2$ transition in light nuclei is the C^{12} $16.1 \rightarrow 0$ transition.[21]

The motivation for the present work was the desire to enable a more detailed comparison between theory and experiment as discussed in the Introduction. Such a comparison will be made in a forthcoming publication.[22]

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[20] A. R. Poletti, E. K. Warburton, and D. Kurath, Phys. Rev. (to be published).

[21] R. E. Segel and M. J. Bina, Phys. Rev. **124**, 814 (1961).

[22] H. J. Rose, O. Häusser, and E. K. Warburton (to be published).