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Angular correlation study of the proton decay of ^{14}N states below 11 MeV*

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Angular correlations of decay protons from 15 unbound ^{14}N states below $E_x = 11$ MeV were measured in the reaction $^{12}C(^3He,p)^{14}N(p')^{13}C_{g.s.}$. Incident ^{3}He energies of 12.0, 13.5, and 14.0 MeV were used in the various measurements. The decay protons (p') were detected in coincidence with reaction protons (p) emitted at 0° to the beam direction. The correlations were fitted to a theoretical expression containing adjustable parameters describing the ^{14}N substate populations and the angular momentum coupling in the $^{13}C + p$ system. Where two orbital angular momenta were allowed in the decay channel, generally only the lower allowed value was considered. Our results are compared with previous work and are shown to strengthen several existing J^π assignments. New assignments are: 10.06 MeV, $J^\pi = 3^+$ or $J \geq 4$; 10.81 MeV, $J^\pi = 5^+$. The f-/p-wave mixing in the decay of the 9.17-MeV 2^+, $T = 1$ state is consistent with previous $^{13}C(p, \gamma)$ experiments; for the 10.43-MeV second 2^+, $T = 1$ state, $\Gamma_{l=3} < (2.7 \times 10^{-3})\Gamma$. The measured magnetic substate parameters are compared with the predictions of a simple direct-interaction model of the (^{3}He,p) reaction. A recent weak-coupling model calculation of ^{14}N levels is reviewed in the light of the new results.

[NUCLEAR REACTIONS $^{12}C(^3He,p)^{14}N(p')^{13}C$(g.s.), $E = 12.0$, 13.5, 14.0 MeV; measured p, p' coin., $I_{p'}(\theta_{p'})$, $\theta_p = 0°$. ^{14}N-deduced J, π, $\delta(l_{p'})$, channel spin, magnetic substate populations. Magnetic spectrometer, sequential reaction.]

I. INTRODUCTION

Angular correlation measurements involving decay particles from unbound states which have been populated by a nuclear reaction in an axially symmetric geometry have been used for some time to determine spins.[1] Such measurements are analogous to the well-known γ-ray angular correlation technique denoted Method II by Litherland and Ferguson.[2] The interpretation of γ-ray angular correlations typically involves the consideration of one or more continuous parameters, such as a multipole mixing ratio or a magnetic substate population parameter.[3] In contrast, in most of the particle-decay angular correlation experiments reported to date, the correlations are essentially uniquely determined by the J^π of the decaying state; where such measurements are possible, the spin of an unbound state can usually be measured in a model-independent manner. The present work was undertaken to explore the feasibility of extracting useful spectroscopic information from particle-decay angular correlation measurements in the more general case involving several continuous parameters. In particular, these are a magnetic substate population parameter and a parameter describing the coupling of the angular momenta in the decay channel. Related work has been performed by Young, Lindgren, and Reichart[4] and Pronko, Hirko, and Slater[5] in studies of states in ^{10}B and ^{14}O, respectively.

The reaction studied in the present work was $^{12}C(^3He,p)^{14}N(p')^{13}C_{g.s.}$. [Under the experimental conditions of the present work the $^{12}C(^3He, 2p)^{13}C$ reaction is known[6] to proceed predominantly by a sequential mechanism through proton-unbound states in ^{14}N.] Angular correlations were measured for most of the proton-unbound levels of ^{14}N below $E_x = 11$ MeV. The decay protons (p') were detected in time coincidence with reaction protons (p) emitted at zero degrees with respect to the incident beam direction. A preliminary report of the experiments is given in Ref. 7. Also, the results for the 10.81-MeV 5^+ state have been published separately, together with a brief description of the method.[8] In the following, the results of the remainder of the measurements are presented and the experimental arrangement and analysis are discussed in detail.

The extensive literature relating to ^{14}N was reviewed by Ajzenberg-Selove in 1970.[9] The principal source of information for the 19 known ^{14}N states above the threshold for proton emission at $E_x = 7.55$ MeV and below 11 MeV has been through the study of resonances in the $^{13}C(p, p)^{13}C$ and $^{13}C(p, \gamma)^{14}N$ reactions; of these 19 states only those at 10.06 and 10.81 MeV[10] have not yet been observed in one or both of these reactions. The radiative decays of the unbound states at 7.97, 8.49, 8.96, 9.17, and 10.81 MeV have also been studied with the $^{12}C(^{3}He, p\gamma)^{14}N$ reaction.[8,11,12]

Levels in ^{14}N below $E_x \cong 11$ MeV with isospin $T=1$, and $T=0$ levels below ~9 MeV, can be described[13,14] as arising from (a) configurations entirely within the p shell, (b) the coupling of two s, d nucleons to a spinless core, or for negative parity states, (c) the weak coupling of an s, d proton to low-lying negative-parity states in ^{13}C. However, additional states at higher excitations can arise, for example, from the coupling of s, d nucleons to a nonzero spin core. Recently, Lie[14] has presented a calculation of ^{14}N levels based on the weak-coupling model of Ellis and Engeland[15] which includes such core-excited configurations as well as those mentioned above. Lie's calculation is in good agreement with the known properties of all of the bound states and most of the unbound states below 11 MeV. For some of the unbound states below 11 MeV, however, it is difficult to establish the correspondence with the calculated level scheme, and these ambiguities are at least in part due to incomplete or unreliable experimental information. One objective of the present work is thus to contribute to obtaining reliable spin and parity assignments for the ^{14}N states in this excitation region so as to allow a critical comparison with theory.

On the other hand, for states of known spin and parity, it is of interest to attempt to interpret the parameters extracted from the correlation data in terms of the processes involved in the formation and decay of the state. For example, the experimental values of the magnetic substate population parameter will be compared with the predictions of a simple direct-interaction model of the $^{12}C(^{3}He, p)^{14}N$ reaction in Sec. V. Population parameters for the $(^{3}He, p)$ reaction leading to bound states in ^{14}N have previously been measured at a number of bombarding energies below 11 MeV by means of γ-ray angular correlation techniques.[16] It is, in general, more difficult to predict a parameter describing the proton decay, since the decay frequently proceeds via a minor component of the wave function.

II. EXPERIMENTAL PROCEDURE

The experiments were performed with 12.0-, 13.5-, and 14.0-MeV $^{3}He^{++}$ beams from the University of Pennsylvania tandem accelerator. The targets were carbon foils 30–170 $\mu g/cm^2$ thick according to the energy resolution required. Protons from the $^{12}C(^{3}He, p)^{14}N$ reaction were detected at 0° with respect to the incident beam direction by a position-sensitive surface-barrier detector (PSD) located in the focal plane of a magnetic spectrometer. A thin tantalum foil was placed over the face of the PSD to exclude particles heavier than protons. The spectrometer has been described elsewhere[17] in connection with the measurement of γ-ray angular correlations.

Protons resulting from the decay of states in ^{14}N were detected with an array of four 1-mm-thick Si surface-barrier detectors mounted at 20° intervals in the lid of the target chamber; the entire lid could be rotated while the target chamber remained under vacuum. The solid angle subtended by each detector at the target position was $\sim 4 \times 10^{-3}$ sr. Measurements were typically carried out over the angular range $40° \leq \theta_{lab} \leq 165°$; in a few cases the range was extended to $\theta_{lab} = 170°$ using a separate, fixed detector. The integrated charge collected at each set of angles was in most cases 5–10 mC.

A block diagram of the electronics is shown in Fig. 1. The circuitry associated with the PSD is the same as that described in Ref. 17. Crossover timing was employed for the four detectors in the target chamber. The coincidence data were written on magnetic tape on an event-by-event basis under control of a PDP-9 computer; each coincidence event consisted of the outputs of the three analog-to digital converters (ADC's) and the routing module. The computer was also used to generate continuously updated displays of the various spectra.

The coincidence data were subsequently played back using the same PDP-9 computer. Typically the 0° position spectrum was examined first, a window set on the peak of interest, and the time spectrum for that group played back. This procedure serves to reduce considerably time walk with position in the 0° detector. Windows were then set on the true coincidence peak and a representative section of the flat background due to random coincidences. With these requirements the decay-proton spectra were recovered from the tape. Figure 2 illustrates the results of such a procedure. Figures 2(a) and 2(b) show the 0° proton group corresponding to the 8.49-MeV state in ^{14}N and the time spectrum obtained on the second pass, respectively. The width of the time peak is due largely to noise on the low-energy decay-proton pulses ($E_p = 0.5$ MeV at 160°) and to small differences in the crossover times of the four amplifiers. Figure 2(c) shows the four energy spectra obtained on the third pass; random coincidences have not yet been subtracted. In this measurement the fourth detector was fixed at 170° on the opposite side of the beam from the three movable detectors.

The yield of decay protons in each of the energy spectra was determined by simple summation.

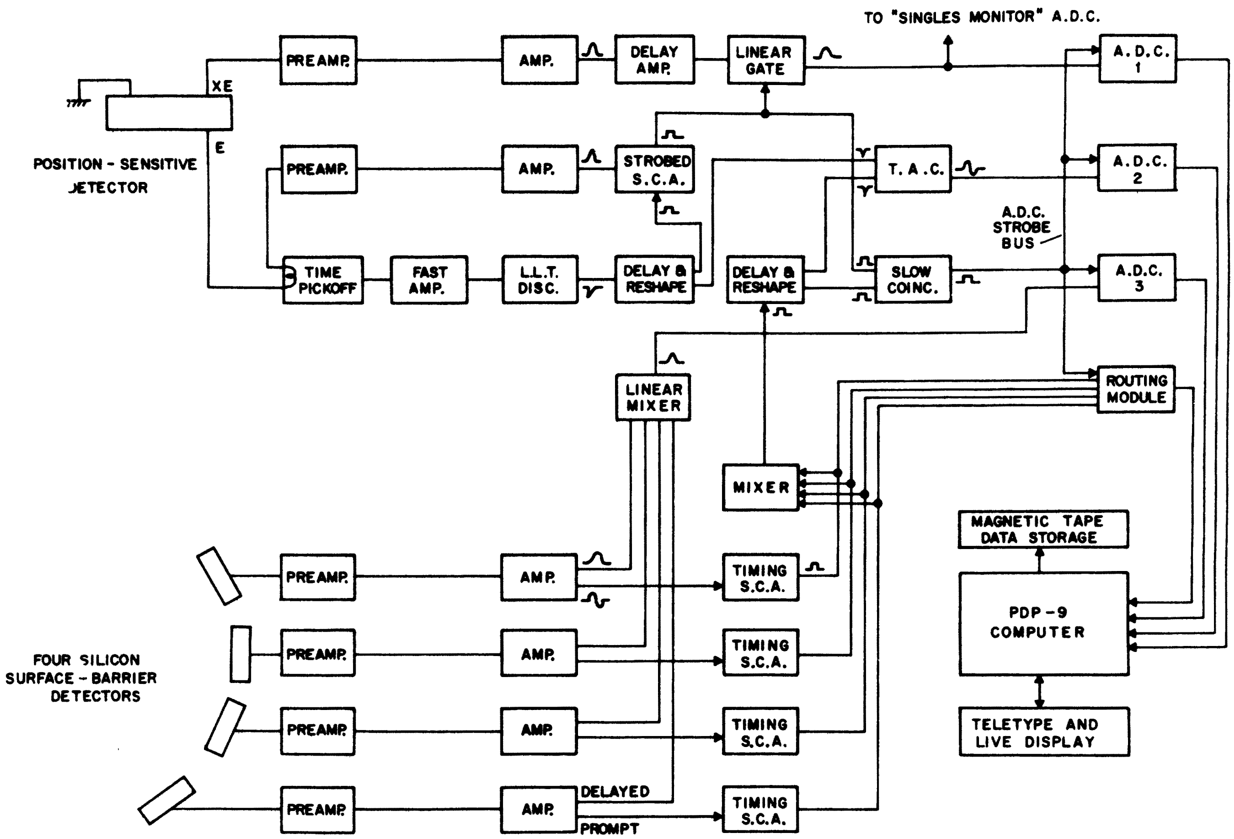

FIG. 1. Block diagram of the electronics employed for the measurements with the array of four detectors.

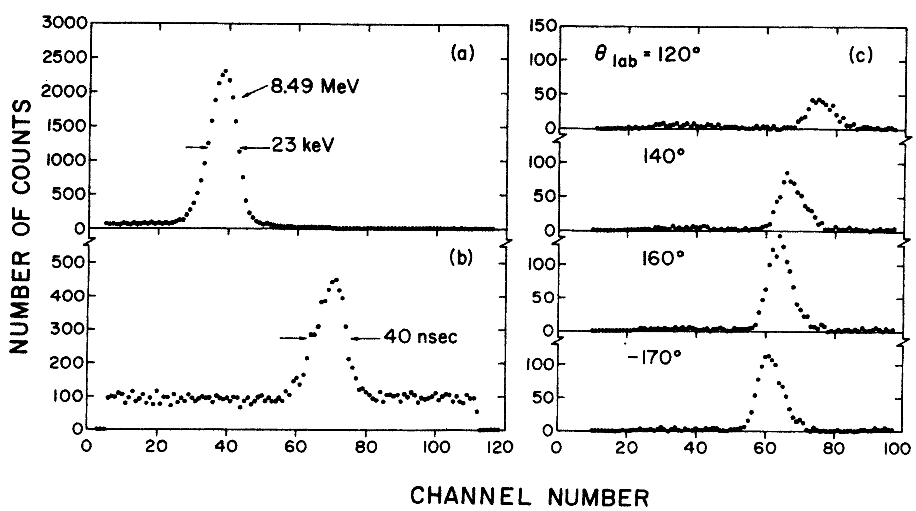

FIG. 2. Spectra illustrating the playback procedure. Shown are (a) the coincident 0° proton spectrum for the 8.49-MeV group, (b) the sum time spectrum, and (c) the four decay-proton spectra.

The yields in the separate runs were normalized using the 0° singles spectrum. In the earliest runs this spectrum was accumulated in a 400-channel monitor analyzer as shown in Fig. 1. Later the acquisition system was modified so that all pulses from the 0° detector were processed by the same ADC. A 0° proton spectrum was then written on magnetic tape together with each buffer load of event-by-event coincidence data.

In some of the more recent measurements the decay protons were detected using a "slice detector." This device was developed to facilitate correlation measurements in experiments where the coincidence yield is extremely small.[18] It is essentially equivalent to 16 3×13-mm-high surface-barrier detectors fabricated on a single silicon wafer ~1 mm thick.[18] The slice detector was mounted on the rotatable lid described above, and was cooled to −30°. Viewed from the target it spans an angular range of 55°, and subtends a total solid angle Ω ~12 times that of the total Ω for the four discrete detectors described above. In practice the coincidence count rate was not increased by as large a factor as this solid angle ratio implies, since the beam current was limited to keep the singles count rate below 50 000 counts/sec. A detailed description of the slice detector and associated electronics has been presented elsewhere.[19]

III. DATA ANALYSIS

The decay-proton correlations are described, in general, in terms of three continuous parameters. The first of these specifies the alignment of the unbound ^{14}N state, the second the coupling of the angular momenta in the decay channel, and the third is simply an over-all normalization factor. The ^{12}C(^{3}He, p)^{14}N reaction, with the outgoing reaction proton detected along the beam axis, will populate only the $m=0$ and $m=\pm 1$ magnetic substates of the ^{14}N state formed. Since the beam and target are unpolarized, for a state of definite parity the $m=\pm 1$ substates are equally populated and the alignment is specified by a single number, here taken to be the fractional population of the $m=0$ substate $P(m=0)$, where $P(0)+2P(1)=1$. The population of substates with $|m|>1$ due to the finite solid angle of the 0° detector was considered to be negligible in view of the small effective entrance angles of the spectrometer.[17]

For a ^{14}N state with spin J ($J\neq 0$) and unnatural parity $[\pi=(-)^{J+1}]$ the proton decay to the $J^\pi=\frac{1}{2}^-$ ground state of ^{13}C involves orbital angular momentum $l=J$ and channel spins 0^- and 1^-. The fraction of channel spin zero is then a parameter of the data analysis procedure. For states with natural parity and spin $J\neq 0$ only channel spin one can be formed and the orbital angular momentum $l=J\pm 1$. A completely general treatment would require consideration of an arbitrary coherent mixture of the two allowed l values. In the absence of unusual structure, however, penetrability considerations suggest that the decay will proceed predominantly by the lower allowed l value. We have therefore generally assumed that the decay of a natural-parity state will involve $l=J-1$ only and with this assumption the theoretical correlation is a function of the spin J and the initial alignment only. The possibility of l-value mixing is considered further for specific cases in Sec. IV.

The theoretical correlation is written as a sum over Legendre polynomials

$$W(\theta)=\sum_k A_k P_k(\cos\theta) \tag{1}$$

with coefficients

$$A_k=\sum_{msll'} P(m)(JmJ-m|k0)(-)^{s-m}\overline{Z}(lJl'J;sk) \times\langle J\|l\|s\rangle\langle J\|l'\|s\rangle^* . \tag{2}$$

The sum in Eq. (2) runs over the allowed values of the channel spin s, the orbital angular momenta l, l', and the magnetic substate quantum numbers m; the vector coupling coefficient and $\overline{Z}$ coefficient are defined in Ref. 20, the parameters $P(m)$ are discussed above, and the quantities $\langle J\|l\|s\rangle$ are the reduced matrix elements for the decay from spin J to channel spin s via orbital angular momentum l. In the decay of an isolated state with definite parity, only even values of k have $A_k\neq 0$ and $W(\theta)$ is symmetric about 90°. Also, the triangle conditions[20] applied to the vector coupling and $\overline{Z}$ coefficients in Eq. (2) imply a restriction on the maximum complexity of the angular correlation. In the present case this restriction requires A_k to vanish if $k>2J$; consequently the presence of a significantly nonzero coefficient of the P_k term in a fit of the experimental correlation to Legendre polynomials places a lower limit of $J=\frac{1}{2}k$ on the spin of the unbound state. [For a state with spin J and natural parity the complexity restriction becomes $k\leq 2(J-1)$ if admixtures of orbital angular momentum $l=J+1$ are negligible.]

It may be noted that no correction for the finite solid angle of the decay-proton detectors has been applied in Eq. (2) or in the following. The acceptance angles of the detectors are sufficiently small that the attenuation of the correlations is negligible in comparison to the statistical errors. For example, using the array of discrete detectors the attenuation of the $k=10$ coefficient is estimated[21] to be <2%.

For decays involving only one l value the theoretical correlation reduces to

$$W(\theta)=\sum_{msk} P(m)T(s)(Jm\,J-m\,|\,k0)(-)^{s-m} \times \overline{Z}\,(lJlJ;\;sk)P_k(\cos\theta), \quad (3)$$

where $T(s=0)$ specifies the fraction of channel spin zero and $T(0)+T(1)=1$. A computer program was written to obtain fits to the experimental data using Eq. (3). The fitting procedure is similar to that employed in the analysis of γ-ray angular correlations.[3] For a fixed value of the channel spin zero fraction $T(0)$ it is straightforward to calculate the value of $P(0)$ corresponding to the minimum of the least-square statistic[22]

$$\chi^2=\frac{1}{n}\sum w_i\,[\,Y_i-NW(\theta_i)]^2\,. \quad (4)$$

Here w_i is the statistical weight associated with the data point $(Y_i,\,\theta_i)$, n is the number of degrees of freedom, and N is the over-all normalization factor. The value of N and the uncertainties in $P(0)$ and N are also obtained in closed form. If an unphysical solution was obtained for $P(0)$ by this procedure, the nearest physical value was adopted. That is, $P(0)$ was set equal to zero or unity, and the normalization and χ^2 were evaluated at that value of $P(0)$. For an assumed spin J and parity $\pi=(-)^{J+1}$, the χ^2 minimum was found for a number (typically 20) of equally spaced values of the channel spin parameter $T(0)$ in the interval $(0,1)$. For states with parity $\pi=(-)^{J+1}$, Eq. (3) is a complete description of the decay process and χ^2 can be interpreted in terms of a confidence limit.[22] If the χ^2 value was never smaller than the 0.1% confidence limit over the entire range of $T(0)$, the spin-parity hypothesis was rejected. In the cases in which an acceptable fit was found, more than one solution for $T(0)$ was typically possible. As discussed in Sec. IV, these ambiguities could sometimes be resolved by comparison with previous experimental work and a unique solution for $T(0)$ and $P(0)$ found.

For an assumed spin J and natural parity $[\pi=(-)^J]$ only channel spin one can be formed and, as remarked above, it was generally assumed that only the lower allowed l value contributes. The value of $P(0)$ corresponding to the χ^2 minimum is then obtained immediately from Eq. (3). It must be emphasized that due to the uncertainty regarding a possible admixture of orbital angular momentum $l=J+1$, the value of χ^2 so obtained cannot be interpreted in terms of a confidence limit. Spin-parity combinations corresponding to natural parity giving an unacceptable fit to Eq. (3) are not rigorously excluded. A further difficulty with the interpretation of χ^2 in terms of a confidence limit in any of the cases discussed here concerns the proper assignment of errors, and this is particularly important when the number of degrees of freedom n is large ($\gtrsim 5$). In addition to the statistical error associated with the number of counts observed in each individual measurement there are various possible systematic errors, and these are difficult to estimate. The experimental errors used included an estimate of the systematic errors which was arrived at by considering the reproducibility of repeated measurements and the results for states of known spin.

In the cases in which a coherent mixture of the two allowed l values was considered Eqs. (1) and (2) become

$$W(\theta)=\sum_{mk} P(m)(Jm\,J-m\,|\,k0)(-)^{1-m} \times\{\overline{Z}(lJlJ;\;1k)+2\delta\cos(\xi_l-\xi_{l+2})\overline{Z}(lJl+2J;\;1k) + \delta^2\overline{Z}(l+2Jl+2J;\;1k)\}P_k(\cos\theta), \quad (5)$$

where an over-all factor has been omitted. Here δ is the mixing ratio for the two l values and the factor $\cos(\xi_l-\xi_{l+2})$ in the interference term accounts for the different nonresonant phase shifts of the two partial waves. The quantities ξ are defined in Ref. 20; they were evaluated using standard graphs of Coulomb functions.[23] The procedure for obtaining fits of the data to Eq. (5) was similar to that employed for the unnatural-parity states, except that $\arctan\delta$ rather than $T(0)$ was varied in discrete steps.

IV. RESULTS

Decay-proton correlations were measured for 15 of the 19 known[9] unbound states below 11 MeV. A high-resolution proton spectrum from the ^{12}C(^{3}He, p)^{14}N reaction for the excitation region studied is given in Ref. 24. The broad level at $E_x=8.8$ MeV was not observed in the present experiment; this is consistent with the $J^\pi=0^-$, $T=1$ assignment for this level[9] and selection rules[25] for direct excitation in the ^{12}C(^{3}He, p)^{14}N reaction. No measurement was attempted for the lowest unbound states at $E_x=7.97$ and 8.06 MeV. The J^π assignment for the 7.97-MeV state has recently been reviewed[11] and that for the 8.06-MeV state is firmly established.[9] Finally, as discussed further below, a correlation was obtained for only one member of the 16-keV doublet[9] at 8.97 MeV.

The fits shown with the measured correlations were obtained, unless otherwise noted below, using Eq. (3). The data were also fitted to Legendre polynomials, and the coefficients thus obtained are given in Table I. Each correlation was fitted to successively increasing orders of Legendre polynomials and the corresponding values of χ^2 and Fisher's F statistic computed. Using these tests of goodness of fit[22] the coefficients are given to the highest order required to describe each correlation. Also shown in Table I are the ^{3}He energies at which the measurements were made.

In the following the results for the individual states are discussed in turn; except for the 9.51- and 10.43-MeV states the order is that of increasing excitation energy. In the cases in which the quantum numbers of the states are not firmly established we have discussed the implications of the present and previous work for the J^π assignments in some detail. Where the spin and parity are known the measurements of magnetic substate populations and l-value mixing are emphasized.

A. 8.49-MeV state

The 8.49-MeV state has been observed as a weak resonance at $E_p = 1.012$ MeV in the $^{13}C(p,\gamma)^{14}N$ reaction.[26] Detenbeck *et al.*[26] conclude that the only assignment consistent with all of the observed properties of the resonance is $J^\pi = 4^-$ with $T = 0$. However, several of the possible assignments were ruled out because they would imply unusually retarded γ-ray transitions; the fact that such retardation arguments are not completely reliable is presumably the reason the 4^- assignment is listed as tentative in the ^{14}N compilation.[9]

The decay-proton correlation for the 8.49-MeV state (Fig. 3) clearly shows strong forward-backward peaking and pronounced structure, and these features are an immediate indication of high spin. The fit obtained for $J^\pi = 4^-$ using Eq. (3) is also shown in Fig. 3; no other spin-parity combination gave an acceptable fit.

It is important to emphasize that the present data require $J \geq 4$ independent of any assumption concerning the orbital angular momenta involved in the proton decay. This follows from the presence of a significant term in $P_8(\cos\theta)$ in the Legendre polynomial expansion of the correlation (Table I). The previous experiments[9,26] have determined the radiative width for the $8.49 \rightarrow 5.11$-MeV ($J^\pi = 2^-$, $T = 0$) transition. A spin of $J \geq 5$ for the 8.49-MeV state would correspond to an extremely large enhancement for this transition and is therefore definitely excluded. Similarly, the known radiative width would correspond to an $M2$ enhancement of 142 ± 50 Weisskopf units if the 8.49-MeV state were 4^+, and therefore this possibility can also be definitely ruled out. The isospin is fixed as $T = 0$ by the observation[27,28] of the 8.49-MeV state in the $^{12}C(\alpha, d)^{14}N$ reaction. Thus the J^π and T assignment of Detenbeck *et al.*[26] is now firmly established.

The fit shown in Fig. 3 corresponds to a channel spin-zero fraction for the emission or absorption of a proton of ~37% or >75%. Only the latter value is consistent with the γ-ray distribution measured

TABLE I. Legendre polynomial coefficients for the decay-proton correlations. The coefficients are given to the highest order required to describe each correlation. The ^{3}He bombarding energies employed are also shown.

E_x (MeV)	$E_{^3He}$ (MeV)	Legendre polynomial coefficients a_2	a_4	a_6	a_8	a_{10}
8.49	12.0	1.13 ± 0.04	0.95 ± 0.05	0.65 ± 0.06	-0.29 ± 0.05	
8.62	12.0	a				
8.91	12.0	1.10 ± 0.09	0.80 ± 0.11			
8.98	12.0	0.69 ± 0.04 [b]				
9.13	12.0	1.07 ± 0.04	c			
9.17	12.0	1.46 ± 0.11	1.70 ± 0.12			
9.39	13.5	0.95 ± 0.04	0.21 ± 0.06			
9.51	13.5	1.16 ± 0.10	0.40 ± 0.13			
9.70	13.5	0.26 ± 0.06				
10.06	13.5	1.08 ± 0.05	0.64 ± 0.08	0.44 ± 0.08		
10.10	13.5	0.53 ± 0.05	-0.23 ± 0.07			
10.23	13.5	0.49 ± 0.05				
10.43	14.0	0.94 ± 0.03	d			
10.56	14.0	0.43 ± 0.07				
10.81	14.0	1.22 ± 0.03	0.94 ± 0.04	0.82 ± 0.05	0.17 ± 0.06	-0.76 ± 0.06

[a] Isotropic correlation ($a_2 = 0.04 \pm 0.04$).
[b] The a_2 value corrected for the contribution of the 8.96-MeV state is 0.61 ± 0.07.
[c] For fit to order $k = 4$, $a_2 = 1.00 \pm 0.05$, $a_4 = -0.19 \pm 0.08$.
[d] The a_4 coefficient is -0.01 ± 0.04.

by Detenbeck *et al*.[26] [This follows from the Legendre coefficients given for the distribution; the channel spin-zero fraction listed in Table 2 of Ref. 26 is incorrect.] For channel spin-zero fractions >75% the magnetic substate population parameter in the present experiment is $P(0)=0.39\pm0.005$, where the error estimate includes the uncertainty in the channel spin ratio.

Because of the low penetrability of $l=4$ protons, γ-ray emission competes favorably with proton decay for the 8.49-MeV state. From a comparison of the coincidence yield of decay protons with the singles yield in the 8.49-MeV peak at 0° we obtain the width ratio $\Gamma_p/\Gamma=0.73\pm0.10$. This is consistent with the width ratio $\Gamma_\gamma/\Gamma=0.21\pm0.05$ obtained by Gallmann *et al*.[12] from the measurement of coincident protons and γ rays in the $^{12}C(^3He, p\gamma)$-^{14}N reaction.

B. 8.62-MeV state

The 8.62-MeV state is the $J^\pi=0^+$ analog of the second excited states in ^{14}C and ^{14}O.[9] A spin-zero state must exhibit an isotropic correlation, and this is clearly observed. An isotropic correlation is also possible for a $J^\pi=1^+$ or 1^- state.

C. 8.91- and 9.51-MeV states

The 8.91- and 9.51-MeV states are known to be, respectively, the 3^-, $T=1$ and 2^-, $T=1$ members

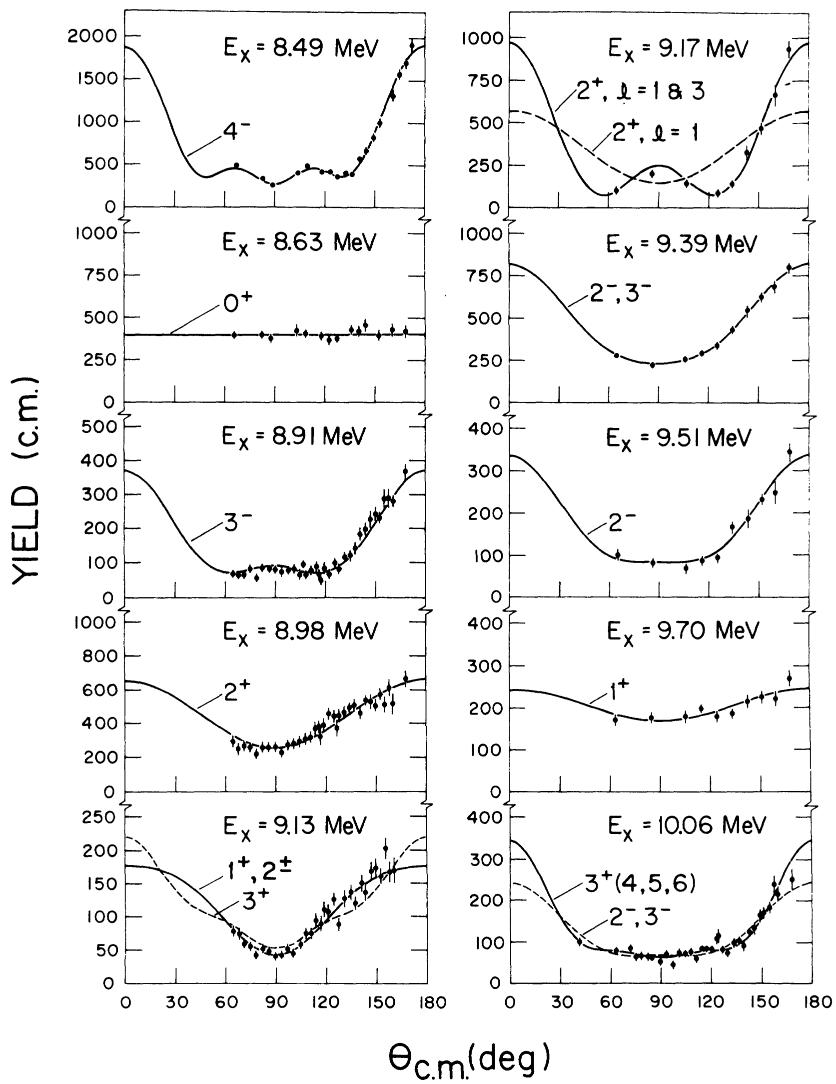

FIG. 3. Angular correlations for the 8.49- to 10.06-MeV states. The best fit curves are calculated from Eq. (3) except for the l-mixed fit to the 9.17-MeV correlation. Where several J^π values label one curve, the corresponding best fits were essentially identical.

of the multiplet resulting from the coupling of a $d_{5/2}$ proton to the ^{13}C ground state. The J^π, T and configuration assignments have been discussed in detail by Warburton, Rose, and Hatch,[29] and are also confirmed by more recent work.[9] In particular, the fact that both states have a d-wave proton width close to the single-particle value strongly supports the suggested configuration.[29] The decay-proton correlations are consistent with the known J^π values, although several other values are possible in each case. For both states the measured correlations determine the population parameter and these are of interest in connection with the mechanism of the (^{3}He,p) reaction. A state with isospin $T=1$ and spin J can be populated in the ^{12}C(^{3}He,p)^{14}N reaction by the direct transfer of an $S=0$, $T=1$ quasideuteron. Since $S=0$, the orbital angular momentum $L=J$, and the parity is restricted to $(-)^J$. Thus the 9.51-MeV 2^-, $T=1$ state, having parity $\pi=(-)^{J+1}$, cannot be populated by direct transfer.[25] This level was in fact not observed in two previous studies

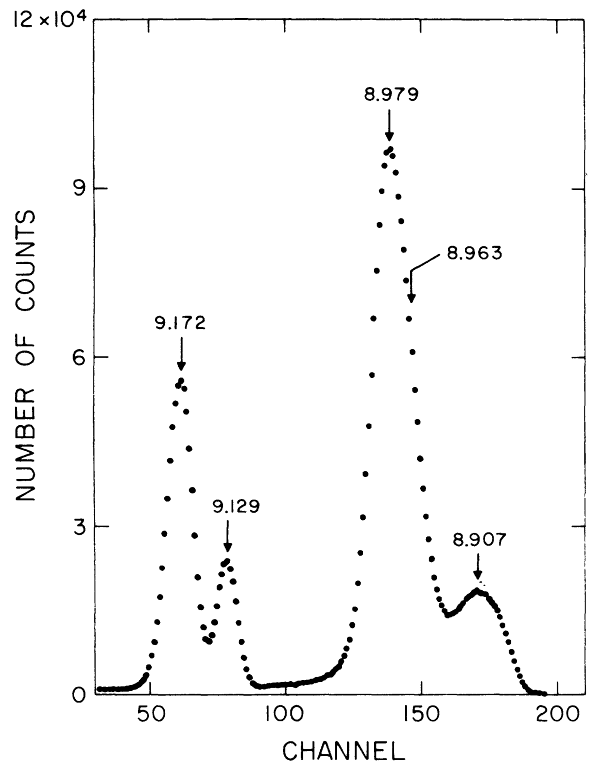

FIG. 4. Zero-degree singles proton spectrum showing the 8.91- to 9.17-MeV groups. The incident ^{3}He energy is 12 MeV. The position-sensitive detector was placed at an angle of 60° to the focal plane to cover the largest practical range of excitation energy (Ref. 17). The resolution is then optimum at only one place on the detector, in this case the position corresponding to the 9.13-9.17-MeV doublet. The excitation energies are taken from Ref. 9.

of the ^{12}C(^{3}He,p)^{14}N reaction.[24,30] In the present experiment, the observed cross section at 0°, although quite small, was sufficient to obtain a correlation.

Both channel spin 0 and 1 are allowed in the decay of the 9.51-MeV 2^- state, but the channel spin-zero fraction has previously been measured and is also calculable from the assumed configuration. (The present data alone require >40% channel spin zero.) The previously measured value, from the ^{13}C(p,γ) study of Warburton, Rose, and Hatch,[29] is (56 ± 14)% channel spin zero, and this is in good agreement with the value 60% expected for the d-wave decay $p_{1/2}\otimes d_{5/2}\rightarrow p_{1/2}$. Warburton, Rose, and Hatch[29] point out that their measurement is also consistent with a $p_{1/2}\otimes d_{3/2}\rightarrow p_{1/2}$ transition, for which the channel spin-zero fraction would be 40%. However, the weak-coupling model calculations[14] indicate that the $p_{1/2}d_{5/2}$ amplitude predominates. Assuming a channel spin-zero fraction of 60%, the measured population parameter is $P(0)=0.76\pm0.06$. If the measured[29] channel spin-zero fraction of (56 ± 14)% is employed, the result is $P(0)=0.85^{+0.15}_{-0.20}$.

Since the decay of the 8.91-MeV 3^- state can occur only by channel spin 1 (and the admixture of g waves in the decay is presumably negligible) the population parameter and its error are obtained immediately from the fit of the correlation to Eq. (3). The result is $P(0)=0.99^{+0.01}_{-0.07}$, in very good agreement with the value $P(0)=1$ expected for $S=0$ quasideuteron transfer in the (^{3}He,p) reaction.

D. 8.96-8.98-MeV doublet

The results of several studies[12,26,27] have definitely established that the 8.96-MeV state is the $(d_{5/2})^2$ $J^\pi=5^+$, $T=0$ state expected[14] near 9 MeV excitation. The 8.98-MeV state has been studied in elastic scattering experiments[31,32]; the work of Latorre and Armstrong[32] excludes the earlier 1^+ result[31] and provides a unique assignment of $J^\pi=2^+$. A $T=0$ isospin assignment is indicated by the absence of corresponding states in ^{14}C and ^{14}O and by comparison with model calculations[14] which place an $(s,d)^2$ 2^+, $T=0$ level near 9 MeV. Both members of the doublet, having two particles outside the ^{12}C core, are expected to be strongly excited in the ^{12}C(^{3}He,p)^{14}N reaction. This has been confirmed in two previous experiments.[24,33]

The intense proton group corresponding to the doublet was examined in singles at $E_{^3\text{He}}=12$ MeV. The proton resolution obtained was sufficient to resolve partially the 8.98- and 8.96-MeV states, and these were found to be excited approximately in the ratio 2:1. A similar ratio is obtained by extrapolating the 11.95-MeV angular distributions of Duray and Browne[33] to 0°. Since the 2^+ state is more strongly excited (and has a natural width $\Gamma = 9$ keV[32]), it was not possible to measure a correlation for the 5^+ state. In the analysis of the coincidence data a window was placed on the half of the 0° proton group towards higher excitation energy, and the correlation thus obtained (Fig. 3) corresponds predominantly (~85%) to decays from the 8.98-MeV 2^+ state. The correlation is seen to be reasonably well fitted assuming $J^\pi = 2^+$ ($l = 1$).

To obtain the population parameter for the 2^+ state a correction was made for the effect of the estimated $(15 \pm 8)\%$ admixture of the 5^+ state. The loss of proton coincidences on account of the known[12] 20% γ-ray decay of the 5^+ state was included in the estimate of the admixture. Assuming that only p waves contribute to the decay of the 2^+ state, and considering that the maximum and minimum possible values of the Legendre coefficient a_2 for the 5^+ state are 1.27 and 1.04, the corrected population parameter is $P(0) = 0.22 \pm 0.14$.

E. 9.13-MeV state

The 9.13-MeV state was one of the three states studied by Detenbeck *et al.*[26] as weak resonances in the $^{13}C(p,\gamma)^{14}N$ reaction. The transition strength for the (>80%) γ-ray decay to the ground state definitely limits the spin of the resonance to $J \leq 3$. Spins $J = 0$ and 3 were rejected on account of the poor fits to the γ-ray angular distribution[26]; for $J^\pi = 3^+$, however, the rejected fit corresponds to a χ^2 probability of 5%. Of the remaining $J = 1, 2$ possibilities Detenbeck *et al.* chose $J^\pi = 2^-$ with $T = 0$ as the only assignment consistent with the absence of γ-ray transitions to states other than the ground state.

The decay-proton correlation for this level was measured twice at nominally the same bombarding energy (±50 keV). In the first measurement the fit of the correlation to Legendre polynomials indicated a nonzero a_6 coefficient, which would rule out $J^\pi = 2^-$. However, the statistics were quite poor on account of the relatively small (^{3}He, p) cross section and the necessity for a thin target. Therefore we remeasured the correlation using the 16-slice detector in place of the array of discrete detectors. The 0° singles position spectrum for this measurement, Fig. 4, illustrates the resolution employed in both runs. In this second correlation (Fig. 3 and Table I) the a_6 Legendre coefficient is consistent with zero. The anisotropy of the correlation definitely excludes $J = 0$ and $J^\pi = 1^-$ (with $l = 0$). Spin $J = 3$ with either parity is rejected by the fits obtained to Eq. (3); the fit for 3^+ gave the lowest unacceptable χ^2 and is shown in Fig. 3. The choices $J^\pi = 1^+$ and $2^\pm$ all gave good fits to these data. A model-dependent argument can be made against 1^+ and 2^+ since these J^π values require $P(0) > 0.7$ and $P(0) = 1.0^{+0.0}_{-0.06}$, respectively, while the population parameters predicted for a direct (^{3}He, p) reaction (Sec. V) are 0.33 and 0.0. It seems unlikely that these discrepancies, at least for the 2^+ case, could be due to nondirect mechanisms in the (^{3}He, p) reaction. For $J^\pi = 2^-$, the best fit corresponds to a channel spin-zero fraction of ~35% or 100%; however, only the latter value is consistent with the γ-ray angular distribution of Detenbeck *et al.*,[26] and the population parameter is then 0.35 ± 0.01.

The apparently inconsistent results obtained in the two measurements described above suggest the possibility of an unresolved doublet at $E_x = 9.13$ MeV. There is additional evidence which supports this idea. Some decay-proton correlations have been obtained in this laboratory in which the ^{14}N levels were excited in the $^{12}C(^6Li, \alpha)$-^{14}N reaction.[34] These data can be analyzed in the same manner as described herein, except that in the case of a natural-parity ^{14}N state, only the $|m| = 1$ magnetic substates can be formed.[34] Among these data the correlation for the 9.13-MeV level, when fitted to Legendre polynomials, had a significantly nonzero a_6 coefficient in agreement with the first of the two results discussed above. Also, McGrath[35] has studied the $^{10}B(^6Li, d)$ and $^{10}B(^7Li, t)$ reactions to a number of ^{14}N levels at $E_{Li} = 3.05$ MeV (center of mass). The 9.13-MeV group was found to dominate the spectra from both reactions. Since the total cross sections for many of the levels were roughly proportional to $(2J + 1)$, the unusually large yield for the 9.13-MeV group might be due to the presence of an additional, previously unknown, state at this excitation energy.

F. 9.17- and 10.43-MeV states

The 9.17- and 10.43-MeV states were first observed as prominent resonances in the $^{13}C(p,\gamma)^{14}N$ reaction.[9] By about 1960 the spin and parity of both states had been established as $J^\pi = 2^+$ from the radiative capture and proton elastic scattering experiments.[9] The isospins must be $T = 1$ in view of the strong $M1$ γ-ray transitions to the ground and 6.44-MeV states and the selection rules for dipole radiation in self-conjugate nuclei.[36]

In 1960 Warburton and Pinkston,[13] in discussing shell-model configurations in $A = 14$ nuclei, noted that two 2^+, $T = 1$ states are expected near 9 MeV in ^{14}N. These result from the coupling of p-shell nucleons (p^{10}) or the coupling of two nucleons to an inert ^{12}C core $[p^8(s,d)]$. However, only the p^{10} 2^+, $T=1$ state would have a strong g.s. $M1$ transition.[13] Since the observed g.s. transition rates for the 9.17- and 10.43-MeV states are each about one half of that predicted for the p^{10} configuration, Warburton and Pinkston concluded that the 9.17- and 10.43-MeV states are formed from approximately equal amplitudes of the p^{10} and $p^8(s,d)$ configurations. Warburton and Pinkston[13] were also able to explain the observation[37] that the proton reduced width of the 9.17-MeV state is ~100 times smaller than that of the 10.43-MeV state. Thus if the wave function of the ^{13}C ground state contains a small $p^7(s,d)$ component, there are two amplitudes for p-wave proton capture (or decay) and these can interfere; if the interference is destructive for the 9.17-MeV state it will be constructive for the 10.43-MeV state. The strong cancellation of the p-wave amplitude for the 9.17-MeV state allows f-wave proton emission to contribute significantly to the total width; the p- and f-wave mixing has been studied by Segel *et al.*[38] and by Prosser, Krone, and Singh[39] by means of the $^{13}C(p,\gamma)$ reaction. For the 10.43-MeV state the proton elastic scattering results[31] set an upper limit of $\Gamma_{l=3} < 0.05\Gamma$ on the f-wave admixture. It is noteworthy that the mixing of the two 2^+, $T=1$ configurations originally suggested by Warburton and Pinkston[13] is also supported by the results of more recent transfer reaction experiments. Thus the 9.17- and 10.43-MeV states are each strongly excited in two-nucleon transfer reactions on ^{12}C and in neutron pickup from ^{15}N, through the p^8-(s,d) and p^{10} components in their wave functions, respectively.[24,30,40]

The form of the angular correlation for proton decays involving a coherent mixture of l values has been discussed in Sec. III. The contribution of the hard-sphere phase shift to the quantity $\cos(\xi_l - \xi_{l+2})$ in Eq. (5) depends upon the channel radius assumed for the p-^{13}C system. The channel radius most frequently adopted in the analysis of p-^{13}C resonance experiments is $R=4.7$ fm $[=1.4(13^{1/3}+1)$ fm$]$. The factor $\cos(\xi_1-\xi_3)$ is then 0.78 for the 9.17-MeV state. However, Prosser, Krone, and Singh[39] employed the value $\cos(\xi)=0.86$, corresponding to $R=3.72$ fm. Allowance is made for uncertainties in the $\cos(\xi)$ factor in the following.

Figure 5 shows the values of the reduced Legendre coefficients $a_2 = A_2/A_0$ and a_4 as a function of the f/p mixing ratio δ and the magnetic substate population parameter $P(0)$. The experimental values of a_2 and a_4 from the least-squares fit to the data are also shown in Fig. 5; the shaded region extends to ±1 standard error from the experimental value. It is apparent that the measured values of a_2 and a_4 for the 9.17-MeV state require approximately equal amplitudes of p- and f-waves and that the state is strongly aligned at $E_{^3He}=12$ MeV. Total alignment, $P(0)=1.0$, is expected if the $^{12}C(^3He,p)^{14}N$ reaction corresponds to the direct transfer of an $S=0$, $T=1$ cluster to ^{12}C. The dependence of χ^2 on the mixing ratio δ is shown in Fig. 6. At each value of δ the population parameter and normalization have been adjusted to give the optimum fit to the correlation. Varying also the $\cos(\xi)$ factor from 0.74 to 0.86, all of the acceptable fits (>1% confidence) correspond to $P(0)>0.8$ and mixing ratios in the interval $(-6.3 < \delta < -0.38)$. This range of mixing ratios is in agreement with the work of Prosser, Krone, and Singh[39] who give $\delta = -0.70 \pm 0.26$ as the value most nearly consistent with their several measured γ-ray distributions. For $\delta=0.70$ [and $\cos(\xi)=0.86$] the best fit to the decay-proton correlation cor-

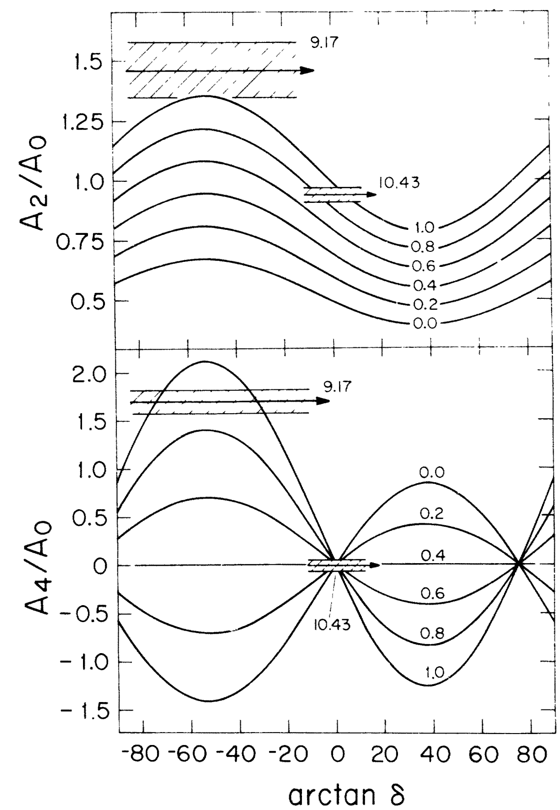

FIG. 5. Reduced Legendre coefficients a_2 and a_4 for the decay of the 9.17- and 10.43-MeV 2^+ states by $l=1$ and 3 proton emission. The curves are calculated from Eq. (5) with $\cos(\xi_1-\xi_3)=0.78$. The abscissa gives the arctangent of the f/p mixing ratio δ, and each curve is labeled with the corresponding population parameter P(0). The experimental Lengendre coefficients and their errors for the two correlations are also shown.

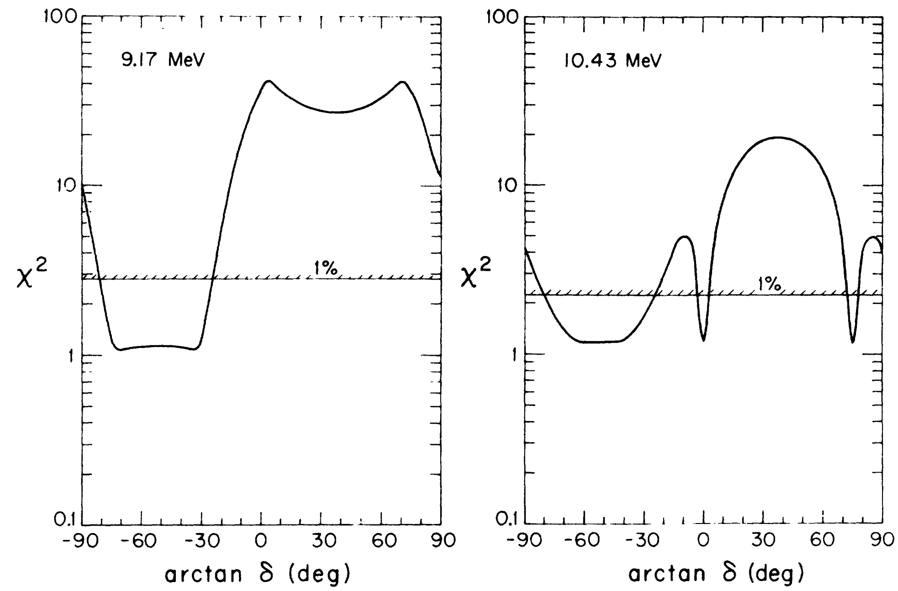

FIG. 6. The goodness-of-fit parameter χ^2 *versus* the arctangent of the f/p mixing ratio δ for the 9.17- and 10.43-MeV states. The cos(ξ) factor is 0.78. At each value of δ the population parameter and the normalization were varied to give the best fit to the data. The value of χ^2 corresponding to 1% confidence (Ref. 22) is also shown.

responds to $P(0)=0.92$, and these values were used to calculate the fit shown in Fig. 3; the dashed curve shows the best fit for 2^+ obtained assuming no l-value mixing.

In contrast to the result for the 9.17-MeV state, the correlation for the 10.43-MeV second 2^+, $T=1$ state is very well fitted assuming pure p-wave proton emission. This is of course expected in the Warburton-Pinkston model[13] since the p-wave interference is now constructive. As was the case for the 9.17-MeV state, strong alignment is observed, with $P(0)=0.89\pm0.04$.

The correlation for the 10.43-MeV state together with the previous restriction[31] on $\Gamma_{l=3}$ provides a strong upper limit on the contribution of f waves to the decay. The factor $\cos(\xi_1-\xi_3)$ in Eq. (5) is nearly the same (for a fixed channel radius R) for the two 2^+, $T=1$ states since the increase in the hard-sphere phase shift towards higher proton energies is offset by an almost equal decrease in the Coulomb phase shift. The curves shown in Fig. 5 therefore also apply to the 10.43-MeV state. From Fig. 5 and the χ^2 plot, Fig. 6, there are three possible solutions for δ, but only that with $\delta\cong 0$ is consistent with the elastic scattering result.[31] The $\delta\cong 0$ solution provides an upper limit on the f-wave admixture of $\Gamma_{l=3}<(2.7\times10^{-3})\Gamma$ at the 1% confidence level. This limit is about 20 times smaller than the earlier estimate.[31] Proton reduced widths $\theta_p^2(l)$ for pure p- or f-wave formation of the 9.17- and 10.43-MeV states have been calculated by Rose.[41] For the 10.43-MeV state the present limit on Γ_3/Γ corresponds to an f-wave reduced width of $\theta_p^2(l=3)<1.6\times10^{-3}$. The same quantity for the 9.17-MeV state is $\theta_p^2(l=3)=(2.3\pm1.1)\times10^{-3}$ using the f/p mixing ratio reported by Prosser, Krone, and Singh.[39]

We note finally that the proton decays of the ^{14}O analogs of the 9.17- and 10.43-MeV states have recently been studied by Pronko, Hirko, and Slater[5] in the reaction ^{12}C(^{3}He, n)^{14}O(p)^{13}N. The results indicate significant f/p mixing in the decay of the 6.59-MeV state but not for the 7.78-MeV state,[5] as would be expected from the correspondence with the ^{14}N states.

G. 9.39-MeV state

The 9.39-MeV state has been observed as a resonance in the elastic scattering of protons by ^{13}C.[32,42] In the more recent work of Latorre and Armstrong[32] the $J^\pi=1^-$ assignment of Zipoy, Freir, and Formularo[42] is ruled out and J^π (9.39 MeV) is shown to be 3^- or 2^-. The angular distribution of protons from the ^{12}C(^{3}He, p)^{14}N reaction populating this state has a shape similar to known $L=1$ transitions in that reaction,[30] and $L=1$ transfer would rule out $J^\pi=3^-$. However, Lie has pointed out that the 3^- possibility would be in better agreement with the weak-coupling model level scheme.[14] Also, the shape of the deuteron angular distribution in the ^{15}N(p, d)^{14}N reaction to the 9.39-MeV state is not that characteristic of a pure $L=2$ transition, but may correspond to $L=4$.[40] The presence of an $L=4$ component in neutron pickup would require $J^\pi=3^-$.

The decay-proton correlation is equally well reproduced for either $J^\pi=2^-$ or 3^-. (These data also allow $J=1$, 2, or 3 with positive parity.) If the 9.39-MeV state has $J^\pi=2^-$ the channel spin-zero fraction is >40%, and this range of values is consistent with that found in the proton elastic scattering analysis[32]; the corresponding population parameter varies with the channel spin in the range 0.45–0.90. If the correct assignment is $J^\pi=3^-$, $P(0)=0.16\pm0.05$. For either 2^- or 3^- the population parameter is in reasonable agreement with that predicted for direct transfer in the $(^3\mathrm{He},p)$ reaction. It would thus appear that neither the present work nor previous experiments, taken together, can distinguish the two possible spin assignments to the 9.39-MeV state.

H. 9.70-MeV state

The decay-proton correlation for the 9.70-MeV state shows a small but definite anisotropy. The small but nonzero a_2 coefficient and the absence of higher terms in the Legendre polynomial fit definitely exclude $J=0$ and $J\geq 2$. An assignment of $J^\pi=1^-$ is also ruled out, unless both s- and d-waves contribute to the decay. Thus the correlation confirms the $J^\pi=1^+$ assignment of Zipoy, Freier, and Formularo,[42] who observed the 9.70-MeV state as a proton elastic scattering resonance. For a 1^+ state the theoretical correlation [Eq. (3)] can be written $W(\theta)=1+\frac{1}{2}[3P(0)-1][3T(0)-1]\times P_2(\cos\theta)$. It follows that the data restrict the parameters $T(0)$ and $P(0)$ to values outside the interval 0.2–0.4.

No isospin assignment is given for the 9.70-MeV state in Ref. 9. In view of the selection rules for direct excitation in the $(^3\mathrm{He},p)$ reaction,[25] the strong population of the 9.70-MeV state in the present experiment confirms previous evidence[27,28,30] that this is a $T=0$ state.

I. 10.06-MeV state

The excitation of a level at $E_x=10.05\pm0.07$ MeV in the $^{14}\mathrm{N}(\alpha,\alpha')^{14}\mathrm{N}$ reaction was reported by Miller *et al.*[43] in 1956. For some time this level was thought to be the same as that seen as a narrow resonance ($\Gamma\sim 10$ keV) in the $^{13}\mathrm{C}(p,p)^{13}\mathrm{C}$ and $^{13}\mathrm{C}(p,\gamma)^{14}\mathrm{N}$ reactions at $E_x=10.095$ MeV.[31,41] It is apparent in the spectrum of protons from the $^{12}\mathrm{C}(^3\mathrm{He},p)^{14}\mathrm{N}$ reaction published by Holbrow, Middleton, and Focht,[24] however, that two narrow levels are present in this region, at 10.06 and 10.10 MeV. The presence of two states at this excitation energy has not been reported elsewhere. The 10.05-MeV peak seen in the $^{14}\mathrm{N}(\alpha,\alpha')^{14}\mathrm{N}$ reaction may correspond to either or both members of the doublet; Miller *et al.*[43] comment that this peak is unusually broad, favoring the latter possibility. The absence of visible structure at $E_p=2.70$ MeV in the proton elastic scattering data[31] sets an upper limit on the width of the 10.06-MeV state of about 1 keV.

The present work provides the first information on the spin of the 10.06-MeV state. The correlation includes data acquired using both the array of discrete detectors and the 16-slice detector. The proton resolution at 0° during the measurements was 20 keV full width at half maximum (FWHM); the necessity of resolving the 10.06- and 10.10-MeV states at 0° made it somewhat difficult to accumulate adequate statistics. The data were very well fitted for $J^\pi=3^+$ and $J=4$, 5, and 6 with either parity; the fit for $J^\pi=3^+$ is shown in Fig. 3 as typical of these. The choices $J^\pi=2^-$ and 3^- gave a considerably poorer fit, as shown; $J^\pi=2^+$ and $J=0$ or 1 are definitely excluded. The above spin and parity restrictions follow also from an examination of the Legendre coefficients (Table I). The fit is significantly improved by the inclusion of the P_6 term, indicating that $(J,l)\geq 3$.

The weak-coupling model calculation[14] predicts $T=0$ states with $J^\pi=3^+$ and 4^+ at $E_x\sim 7.5$ and 9.5 MeV, respectively, which have no experimental counterparts. [The calculated 4^+ state is identified in Ref. 14 with the 10.81-MeV level, now known to have $J^\pi=5^+$ (Ref. 8 and this work).] The 10.06-MeV level is a possible candidate for either of these calculated states.

J. 10.10-MeV state

The proton elastic scattering data of Kashy *et al.*[31] restrict the J^π of the 10.10-MeV state to 1^+ or 2^+, and give its width as $\Gamma=5.5$ keV. A weak g.s. γ-ray transition from this state has been observed by Rose, Riess, and Trost[41]; no additional restriction on its spin was obtained. As in the case of the 10.06-MeV state, the necessity of resolving the 10.06-10.10 doublet limited the statistics which could be obtained. The fit of the correlation to Legendre polynomials was improved by including an a_4 term; the presence of a $k=4$ term would rule out $J^\pi=1^+$, but is consistent with 2^+ if f-wave protons participate in the decay. The possible f/p mixing was studied in the manner described in connection with the 10.43-MeV state. The improved fit shown in Fig. 7 corresponds to the χ^2 minimum found at $\delta=-0.1$ and $P(0)=0.0$. This population parameter is in agreement with that expected for direct transfer to a 2^+, $T=0$ state;

the error in $P(0)$ was estimated to be $^{+0.2}_{-0.0}$. We emphasize that the Legendre coefficient a_2 for the correlation is consistent with a $J^\pi = 1^+$ assignment and only the possible nonzero a_4 favors 2^+. For $J^\pi = 1^+$ the channel spin-zero fraction and population parameter are either both zero or both >0.5. Further information on the spin of this state might be obtained from a reexamination of the elastic scattering resonance with a very thin target.[31,44]

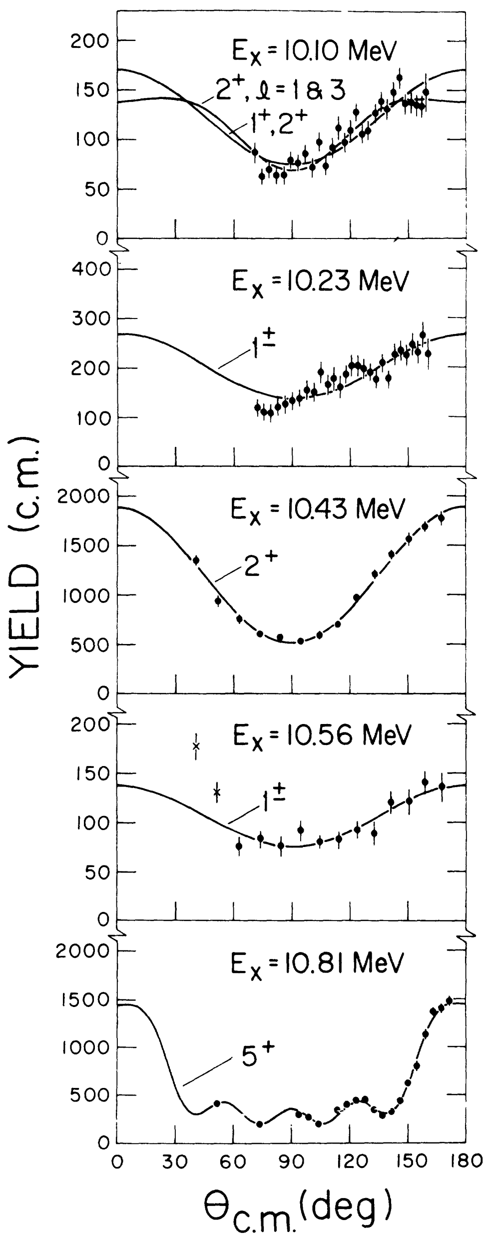

FIG. 7. Angular correlations for the 10.10- to 10.81-MeV states. The fits are discussed in the text.

K. 10.23- and 10.56-MeV states

The 10.23- and 10.56-MeV states were observed as proton elastic scattering resonances by Kashy *et al.*,[31] who reported unambiguous assignments of $J^\pi = 1^-$ for both states. The parity assignment[31] for the 10.23-MeV state has been questioned by Rose, Trost, and Riess.[45] These authors studied the 10.23- to 2.31-MeV γ-ray transition in the $^{13}C(p,\gamma)$ reaction and concluded that only $J^\pi = 1^+$ would be consistent with its observed anisotropy and strength.

Both states were very weakly populated in the present experiment, as shown in Fig. 8. The low reaction yield and the large natural widths ($\Gamma = 94$ and 150 keV for the 10.23- and 10.56-MeV states, respectively[31]) made it difficult to obtain meaningful correlations. Also, there were indications that the assumption of a sequential ($^3He, 2p$) reaction mechanism through isolated ^{14}N intermediate states might not apply here. Kashy *et al.*[31] reported each state to have comparable widths for *s*- and *d*-wave proton emission. If *d*-wave decay is considered, the present experiment cannot distinguish $J^\pi = 1^+$ and 1^-.

The 10.56-MeV state was assumed to correspond

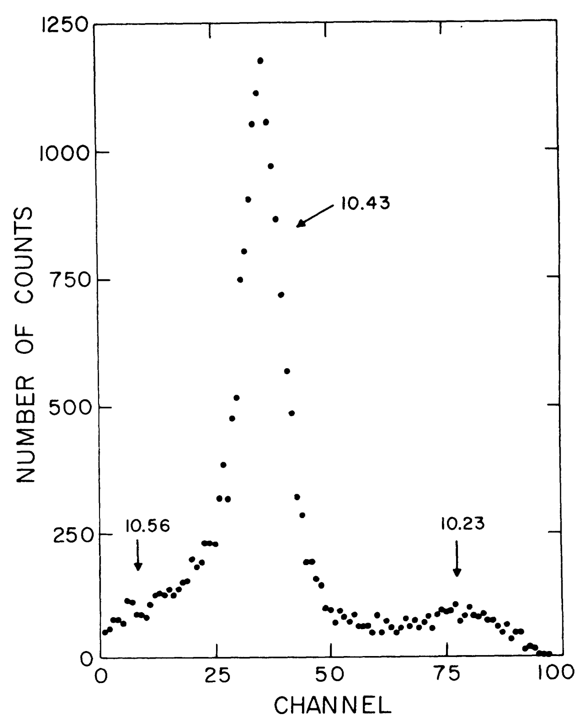

FIG. 8. Zero-degree proton spectrum illustrating the relative yields to the 10.23-, 10.43-, and 10.56-MeV levels at $E_{^3He} = 14$ MeV. Only counts corresponding to true coincidences with decay protons are shown.

to the broad shoulder at the side of the 10.43-MeV peak in the 0° spectrum, Fig. 8. The correlation shows a shallow minimum at 90° with, however, a pronounced rise at the two forward-most points measured. The correlation was fitted to Legendre polynomials with these two points omitted, and the a_2 coefficient thus obtained is consistent with $J=1$ or 2 and either parity.

The fit shown in Fig. 7 for the 10.23-MeV correlation also has the form $W(\theta) \sim 1 + a_2 P_2(\cos\theta)$. There is some indication of an asymmetry about 90° in this correlation. In some additional data acquired at $E_{^3\mathrm{He}} = 14$ MeV the point at $\theta_{\mathrm{c.m.}} = 40°$ shows a pronounced rise. These features are of course an indication that two or more ^{14}N states interfere in this region or that the reaction mechanism is not entirely sequential.

The 10.23- and 10.56-MeV levels were identified by Lie[14] with the 1_2^- and 1_3^- model states in his weak-coupling level scheme. Both model states exhibit the s- and d-wave mixing noted by Kashy *et al.*,[31] on account of the dominant $p_{1/2} \otimes d_{3/2}$ amplitudes in the wave functions.

L. 10.81-MeV state

The decay-proton correlation measured for the 10.81-MeV state requires $J \geq 5$. This result, which is in disagreement with a previous assignment[30] of 4^+, was the motivation for a search, using the ^{12}C(^{3}He, $p\gamma$)^{14}N reaction, for a γ-ray decay from the 10.81-MeV state. The results of the (^{3}He, $p\gamma$) experiment have recently been presented together with a brief description of the present work as relates to that state.[8] For completeness some results are summarized here.

Prior to the present work little was known about the 10.81-MeV state other than that it is excited moderately strongly in two-nucleon transfer reactions on ^{12}C.[27,28,30] Mangelson, Harvey, and Glendenning,[30] in their study of the ^{12}C(^{3}He, p)^{14}N reaction, suggested an assignment of $J^\pi = 4^+$ based on the proton angular distribution and shell-model systematics. Observation of the state in the ^{12}C-(α, d)^{14}N reaction[27,28] determines its isospin as $T=0$.

The coefficient of the P_{10} term in the fit of the decay-proton correlation to Legendre polynomials is -0.76 ± 0.06. Spins $J<5$ and $J^\pi = 5^-$ with $l=4$ are therefore definitely ruled out. The fit obtained for $J^\pi = 5^+$ using Eq. (3) is shown in Fig. 7; the fits for $6^+ (l=5)$ and 6^- are unacceptable. These results are consistent with the (^{3}He, $p\gamma$) angular correlation which requires $J=5$.[8] The 10.81-MeV state γ-ray decays to the 3^+, $T=0$ state at 6.44 MeV, and this mode of decay is also evidence for positive parity.[8]

The fit shown in Fig. 7 corresponds to a channel spin-zero fraction of 30 or 85%; the population parameter is then 0.84 or 0.30, respectively. The (^{3}He, $p\gamma$) angular correlation,[8] which was measured at the same bombarding energy as the decay proton correlation, could, in principle, be used to determine $P(0)$. However, the γ-ray correlation is only weakly sensitive to the population parameter so that it was not possible to resolve the ambiguity.

V. COMPARISON OF THE POPULATION PARAMETERS WITH A DIRECT-REACTION MODEL

As pointed out in Sec. IV, for many of the states studied it was possible to measure the magnetic substate population parameter $P(0)$. Balamuth, Anastassiou, and Zurmühle,[3] in connection with the analysis of γ-ray angular correlations in the ^{40}Ca(^{3}He, $p\gamma$)^{42}Sc reaction, have discussed a simple model of the (^{3}He, p) reaction on a spinless target which allows a definite prediction for the quantity $P(0)$ to be made. The predictions of this simple model were in generally quite good agreement with experiment in the ^{42}Sc study.

The (^{3}He, p) reaction is imagined to take place by the direct transfer to the target of a neutron-proton cluster with orbital angular momentum L and spin S, and with the remaining proton emitted along the beam direction. Spin-orbit coupling in the reaction entrance and exit channels is ne-

TABLE II. Comparison of the measured population parameters with the values predicted from Eq. (6) for a direct (^{3}He,p) reaction. The value $P(0)=1$ corresponds to 100% population of the $m=0$ magnetic substate.

E_x (MeV)	J^π	T	L (^{3}He,p)	$P(0)$ calc.	$P(0)$ exp.
8.49	4^-	0	3(5)	0.44	0.39 ± 0.005
8.91	3^-	1	3	1.0	$0.99^{+0.01}_{-0.07}$
8.98	2^+	0	2	0.0	0.22 ± 0.14
9.13	2^-	0	1(3)	0.40	0.35 ± 0.01
9.17	2^+	1	2	1.0	>0.8
9.39	$\{3^-$	0	3	0.0	0.16 ± 0.05
	2^-	0	1(3)	0.4	$0.45 - 0.90$
9.51	2^-	1	Ref. a	Ref. a	$0.85^{+0.15}_{-0.20}$ [b]
10.10	$\{2^+$	0	2	0.0	$0.0^{+0.2}_{-0.0}$
	1^+	0	0(2)	0.33	0.0, >0.5
10.43	2^+	1	2	1.0	0.89 ± 0.04
10.81	5^+	0	4(6)	0.45	$\{0.30 \pm 0.05$
					0.84 ± 0.04

[a] This state cannot be populated by direct transfer in the (^{3}He,p) reaction (Ref. 25).

[b] This value corresponds to the channel spin-zero fraction of (56 ± 14)% measured by Warburton, Rose, and Hatch (Ref. 29). If $T(0) = 0.60$ is assumed, the result is $P(0) = 0.76 \pm 0.06$.

glected. The relative population of the $m=0$ substate for a state with spin J is then determined by the relation[3]

$$P(0)/P(1)=(L0\,S0\,|\,J0)^2/(L0\,S1|\,J1)^2 \qquad (6)$$

together with the normalization condition $P(0)+2P(1)=1$. A particularly simple example is when the transferred cluster is a quasideuteron, with spin $S=0$ and isospin $T=1$; the state populated is then fully aligned, $P(0)=1.0$, as in the well-known case of reactions such as $^{12}C(^{12}C, \alpha)^{20}Ne$ involving only spinless particles.

The experimental values of $P(0)$ are compared with those calculated from Eq. (6) in Table II. Since the ^{12}C ground state has $T=0$, the spin of the transferred cluster is either $S=0$ or $S=1$ for $T=1$ and $T=0$ states in ^{14}N, respectively. For states with unnatural parity and $T=0$, two values of $L(L=J\pm1)$ are allowed by the conservation of angular momentum and parity, and in these cases it was assumed that $L=J-1$.

Heusch and Gallmann[16] have recently presented an extensive series of population parameter measurements in the reaction $^{12}C(^{3}He, p\gamma)^{14}N$. The alignments were reported for five bound ^{14}N states at 32 incident energies in the range $3\leq E_{^3He}\leq 11$ MeV, and the protons were detected at both 0 and 180°. The measured alignments exhibit strong fluctuations with changes in bombarding energy of the order of 1 MeV, and the values do not generally agree with the direct reaction prediction, Eq. (6). The strong fluctuations in alignment and the lack of agreement with Eq. (6) are apparent at both $\theta_p=0$ and 180°, and also persist to the highest bombarding energy studied.

Heusch and Gallmann[16] interpret their results as indicating that the $(^3He, p)$ reaction cross section for their work is mainly due to compound-nuclear processes. Since in the present work the alignments of the unbound states were not measured as a function of bombarding energy, it is somewhat difficult to compare our results with those of Ref. 16. Insofar as it is possible to make the comparison, it would appear that the agreement with the direct reaction prediction [Eq. (6)] is significantly better in the present work. This improved agreement can probably be attributed to the increasing importance of the direct reaction mechanism at the somewhat higher bombarding energies employed here. It is worth mentioning that for those states listed in Table II where the predictions for a direct or compound nucleus reaction[16] are significantly different, the results agree quite well with the direct reaction prediction. This is particularly striking for the three $T=1$ states at 8.91, 9.17, and 10.43 MeV.

VI. DISCUSSION

The present work demonstrates that particle-decay angular correlation measurements can be effective in determining spins even when several continuous parameters enter into the analysis. For example, the 8.49- and 10.81-MeV states have $J\geq4$ and $J\geq5$, respectively, simply on account of the complexity of their correlations. Unique assignments of $J^\pi=4^-$ and 5^+ are obtained if it is assumed that the lower-allowed orbital angular momentum value is favored in the decay of a natural-parity state. It is noteworthy that high spin states are often difficult to study in resonance experiments, and it is for these states that the present method seems to be the most effective. Of course the technique can also be applied in nuclei such as ^{14}O which cannot be reached in resonance experiments.[5]

The correlations were found to be sensitive functions of the ^{14}N substate populations in a number of cases. The possibility of applying such measurements to the study of reaction mechanisms was illustrated in Sec. V. The results for the 9.17- and 10.43-MeV 2^+, $T=1$ states have demonstrated that the correlations can also be sensitive probes of orbital angular momentum mixing. In the cases in which such mixing occurs, its presence provides insight into the structure of the state involved.

Lie's weak-coupling-model calculation[14] seems to describe ^{14}N very well up to at least 11 MeV. The calculation is based on an elaboration by Ellis and Engeland[15] of the idea of Arima, Horiuchi, and Sebe[46] that the particle-hole interaction should be weak compared to the interaction between particles in the same oscillator shell. The basis states of the calculation[14] are combined eigenstates of $n_p\leq3$ particles in the s,d shell and n_h holes in the p shell,

$$\psi=[\,|(sd)^{n_p}\gamma_pJ_pT_p\rangle\,|(p)^{n_h}\gamma_hJ_hT_h\rangle\,]_{J,T,T_z}\,. \qquad (7)$$

The γ's here denote quantum numbers used to classify the separate particle and hole eigenfunctions. All particle-hole configurations having an unperturbed excitation energy of <20 MeV are included in the basis. The particle-hole interaction V_{ph} is diagonalized after eliminating the spurious states. Lie attributes some of the quantitative deficiencies of the calculation to the neglect of the tensor interaction in V_{ph}, which was taken to be the Gillet potential.[47] In the following the comparison between Lie's calculated level scheme and the experimental levels is reviewed in the light of the present results.

For the negative-parity levels the correspondence between the calculated and experimental

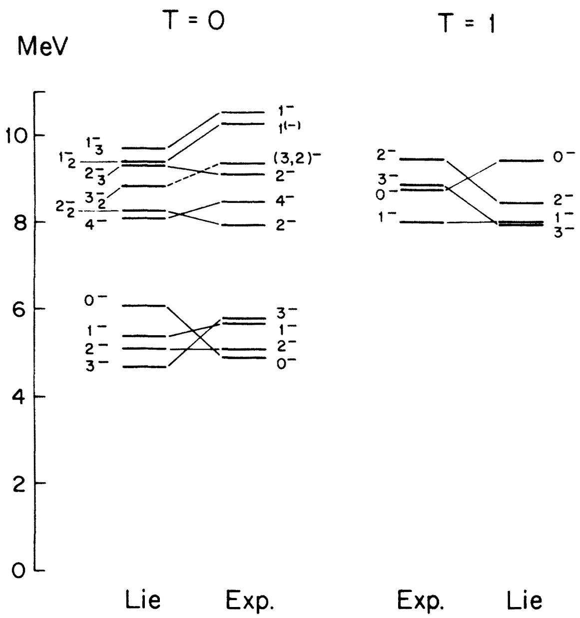

FIG. 9. Comparison of the Lie weak-coupling model level scheme (Ref. 14) with experiment for the negative-parity levels. The J^π values for the bound levels ($E_x < 7.5$ MeV) are firmly established (Ref. 9); the assignments for the unbound levels are discussed in the text.

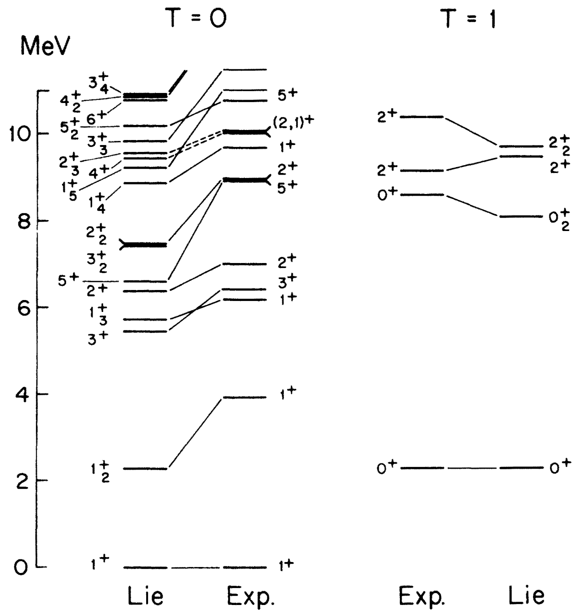

FIG. 10. Comparison of the Lie calculation (Ref. 14) with experiment for the positive-parity levels. The 3_3^+, 3_4^+, and 4_2^+ model states were associated by Lie with levels above 11 MeV; the 3_2^+ and 6_1^+ states have no known experimental counterparts. The 4_1^+ and 2_3^+ model states are tentatively identified with the 10.06- and 10.10-MeV states, as discussed in the text. See also the caption for Fig. 9.

levels (Fig. 9) remains the same as that suggested by Lie.[14] The results of the present work and those of Ref. 11 have provided additional evidence for the assignments $J^\pi = 2^-$, 4^-, and 2^- to the 7.97-, 8.49-, and 9.13-MeV states, respectively. We were not able to rule out either of the two possible spins (3^-, 2^-) for the 9.39-MeV level, and the parity of the 10.23-MeV level also remains in question.

Several modifications are incorporated in Fig. 10, showing the positive-parity levels. First, the 10.81-MeV level has $J^\pi = 5^+$ and is identified with the 5_2^+ model state. The correct prediction of a 5^+ state in this excitation region is an important feature of the weak-coupling calculation.[14] The 4_1^+ model state (previously identified[30,14] with the 10.81-MeV level) may correspond to the 10.06-MeV level, since this has been shown to have $J^\pi = 3^+$ or $J \geq 4$. Also, we have tentatively identified the 10.10-MeV level with the 2_3^+ state since the 2^+ possibility is favored in the present work.

We note that the 3_2^+ and 6_1^+ states in Lie's calculation[14] have no apparent experimental counterparts. It is important that these be identified if in fact they exist. It should be recalled in this context that our results suggest that the 9.13-MeV level may be a doublet, with one member having $(J, l) \geq 3$. Also, we hope that the apparent success of the weak-coupling calculation[14] will motivate further studies of $^{13}C + p$ resonance reactions. A reexamination of the proton elastic scattering resonances corresponding to the 9.39-, 10.10-, and 10.23-MeV levels might resolve the remaining uncertainties in the J^π assignments for these levels. The radiative decays of the 9.39- and 10.06-MeV levels (which are presently unknown[9]) might be observable in the $^{13}C(p, \gamma)$ reaction. Knowledge of these decays could provide additional information on the spins of these levels and would be a further test of the weak-coupling model[14] wave functions.

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