analyses explain fairly successfully all nucleon-nucleon interactions up to several hundred Mev in terms of central, tensor, and spin-orbit forces that are derived from potentials with a Yukawa shape and a hard central core[19] or from the Gartenhaus potential plus a spin-orbit potential.[20]

ACKNOWLEDGMENTS

We are indebted to F. J. Edeskuty for assistance in the weight determinations of the cell, to Max Goldstein for supervising some of the air-scattering calculations, to Herman Kahn of the Rand Corporation for the Monte Carlo calculation of cell inscattering, and to James H. Coon for the use of his transmission cells.

PHYSICAL REVIEW VOLUME 114, NUMBER 1 APRIL 1, 1959

$C^{13}(p,\gamma)N^{14}$ 1.47- and 2.11-Mev Resonances and the Odd-Parity Levels of Mass 14*

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(Received November 11, 1958)

A study has been made of the γ rays emitted by the 8.9- and 9.5-Mev levels of N^{14} using the $C^{13}(p,\gamma)N^{14}$ reaction at the 1.47- and 2.11-Mev resonances. The decay schemes of these levels were reinvestigated using a three-crystal pair spectrometer, NaI(Tl) single-crystal measurements, and standard $\gamma-\gamma$ coincidence techniques. The anisotropies relative to the bombarding beam of most of the observed γ transitions were measured using the three-crystal pair spectrometer. The angular distributions of some of the γ transitions were measured using a single NaI(Tl) crystal. Measurements were made of the Doppler shifts of the ground state decay of the N^{14} 5.10-Mev level and the cascade from the N^{14} 5.83-Mev level to the N^{14} 5.10-Mev level. From these Doppler shift measurements the mean lifetime of the N^{14} 5.83-Mev level was found to be in the range $(5\text{-}65)\times10^{-14}$ sec; while an upper limit of 3×10^{-13} sec was set on the mean life of the N^{14} 5.10-Mev level. The results of the study of the γ decay of the N^{14} 9.5- and 8.9-Mev levels combined with the results of earlier measurements give conclusive assignments of 2^-, 3^-, 3, and 2 for the N^{14} levels at 9.50, 8.90, 5.83, and 5.10 Mev. The 5.83-Mev level most probably has odd parity. A tentative assignment of $J=2$ is given to the N^{14} 7.02-Mev level. Evidence is presented, from this and previous investigations, that indicates the N^{14} 8.06-, 8.70-, 8.90-, and 9.50-Mev levels arise from the s^4p^92s and s^4p^9d configurations with the largest contribution being from the $(p_{1/2}2s_{1/2})$ configuration for the 8.06- and 8.70-Mev levels and from the $(p_{1/2}d_{5/2})$ configuration for the 8.90- and 9.50-Mev levels. The analogs of these $T=1$ levels in C^{14} are almost certainly the C^{14} 6.09-, 6.89-, 6.72-, and 7.35-Mev levels, respectively. The $T=0$, s^4p^92s and s^4p^9d states of N^{14} are also discussed. It is proposed that the 4.91-, 5.69-, 5.10-, and 5.83-Mev levels of N^{14} are 0^- and 1^-, $s^4p^92s_{1/2}$ and 2^- and 3^-, $s^4p^9d_{5/2}$ states, respectively.

I. INTRODUCTION

THE experimental work which will be described in this paper consists of a detailed investigation of the γ transitions from the resonances in the $C^{13}(p,\gamma)N^{14}$ reaction at proton energies of 1.47 and 2.1 Mev. These resonances, which correspond to N^{14} levels at excitations of 8.9 and 9.5 Mev, have been previously investigated by the $C^{13}(p,p)C^{13}$ reaction[1–3] and the $C^{13}(p,\gamma)N^{14}$ reaction.[4,5] The proton scattering data of Milne[1] for the 1.47-Mev resonance and of Zipoy *et al.*[2] for the 2.1-Mev resonance showed that these resonances are formed by even-wave protons. The Wigner sum-rule limit rules out capture of protons with orbital angular momentum greater than three, and the complexity of the angular distributions of the elastically scattered protons rules out pure *s*-wave proton formation.[1,2] Therefore, the 1.47-Mev and 2.1-Mev resonances are formed at least partially by *d*-wave protons. Since the C^{13} ground state has[6] $J^\pi=\frac{1}{2}^-$, the possible spin-parity assignments for the N^{14} 8.9-Mev and 9.5-Mev levels are $J^\pi=1^-$, 2^-, or 3^-. The scattering analysis gives a most probable assignment of $J^\pi=3^-$, with 2^- more likely than 1^-, for the 8.9-Mev level,[1] and a most probable assignment of $J^\pi=2^-$, with 3^- more likely than 1^-, for the 9.5-Mev level.[3,7]

The N^{14} 8.9-Mev and 9.5-Mev levels were first investigated by Seagrave[4] who observed the 1.47-Mev and 2.1-Mev resonances in a general investigation of the $C^{13}(p,\gamma)N^{14}$ reaction. Seagrave measured the

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1 E. A. Milne, Phys. Rev. **93**, 762 (1954).

2 Zipoy, Freier, and Famularo, Phys. Rev. **106**, 93 (1957).

3 D. M. Zipoy, Phys. Rev. **110**, 995 (1958).

4 J. D. Seagrave, Phys. Rev. **85**, 197 (1952).

5 Woodbury, Day, and Tollestrup, Phys. Rev. **92**, 1199 (1953).

6 F. Ajzenberg and T. Lauritsen, Revs. Modern Phys. **27**, 77 (1955).

7 The most probable assignment for the 9.5-Mev level was originally given as $J^\pi=3^-$ (reference 2). R. K. Adair (private communication) first showed that the scattering data of Zipoy *et al.* (reference 2) indicated a most probable assignment of $J^\pi=2^-$ rather than $J^\pi=3^-$ for the 9.5-Mev level. The most probable assignment $J^\pi=2^-$ was verified by Zipoy (reference 3).

absolute (p,γ) cross section and the total width Γ of both resonances. In a later investigation, Woodbury *et al.*[5] determined the major γ-decay mode of both resonances and measured the anisotropy relative to the proton beam of the primary γ transition of these decay modes. Woodbury *et al.* observed that the 8.9-Mev level decays to the N^{14} 5.83-Mev level, while the 9.5-Mev level decays to the N^{14} 5.10-Mev level. No other decay modes were observed for either resonance. The anisotropies obtained by Woodbury *et al.* for the $8.9 \rightarrow 5.83$ and $9.5 \rightarrow 5.10$ transitions were both positive. The nonzero anisotropies of these transitions rules out pure *s*-wave formation of the 1.47- and 2.1-Mev resonances, in agreement with the proton scattering experiments.

The strengths of the $8.9 \rightarrow 5.83$ and $9.5 \rightarrow 5.10$ transitions calculated[4,5] from the absolute cross-section measurements of Seagrave[4] are large enough to establish these transitions as predominantly dipole (see Sec. IIIC). Assuming pure dipole radiation, the theoretical anisotropy of the primary γ transition calculated for *d*-wave proton capture and a well-isolated resonance in the $C^{13}(p,\gamma)N^{14}$ reaction is positive if the spins of the resonance level and the final level are the same and negative if the spins are different (see Sec. IVA). The strengths of admixtures of quadrupole radiation in the $8.9 \rightarrow 5.83$ and $9.5 \rightarrow 5.10$ transitions consistent with reasonable values for the quadrupole radiation matrix elements are not large enough to change the sign of the theoretical anisotropies (see Secs. III and IV), so that the anisotropy measurements of Woodbury *et al.*[5] indicate that the 8.9-Mev and 5.83-Mev levels have the same spin, as do the 9.5-Mev and 5.10-Mev levels. These anisotropy measurements, combined with the most probable spin assignments for the 8.9-Mev and 9.5-Mev levels from analysis of the proton scattering data, give most probable spin assignments of $J=3$ and 2 to the 5.83-Mev and 5.10-Mev levels, respectively. However, these spin assignments are not in accord with all the experimental information. There is no other evidence for the spin of the N^{14} 5.83-Mev level, but the theoretical anisotropy calculated[5] under the assumptions mentioned above with $J=3$ for both the resonance level and the final level is in poor agreement with the anisotropy measurement of Woodbury *et al.*[5] for the $8.9 \rightarrow 5.83$ transition. The anisotropy measurement of Woodbury *et al.* for the $9.5 \rightarrow 5.10$ transition is in agreement with the theoretical anisotropy with $J=2$ for both levels; however, an assignment of $J=1$ for the 5.10-Mev level has been suggested[6,8] from other evidence. This evidence will be discussed in Sec. IVC.

One purpose of the present investigation was to resolve these discrepancies and to obtain spin assignments for the N^{14} levels at 9.5, 8.9, 5.83, and 5.10 Mev independent of the most probable spins obtained from previous results, but dependent on the definitely established even-wave proton formation of the 8.9- and 9.5-Mev levels and the absolute cross section measurements of Seagrave.[4]

For both resonances Woodbury *et al.*[5] compared the measured anisotropies of the primary γ transitions to theoretical anisotropies calculated for a well-isolated resonance. The actual anisotropies are subject to the effects of interference with other levels, so that interference of the γ transition to a given level with a γ transition originating from another resonance (or a nonresonant background) and feeding the same level could have an important influence. A search for such interference effects was then an important part of the present investigation. An assumption made in the present comparison of the measured anisotropies of Woodbury *et al.*[5] with the theoretical anisotropies was that the $8.9 \rightarrow 5.83$ and $9.5 \rightarrow 5.10$ transitions are pure dipole in character. The validity of this assumption and the extent of multipole mixing in general for the various transitions observed in the present investigation were carefully considered in the analysis of the results presented in this paper.

In addition to reinvestigating the $8.9 \rightarrow 5.83$ and $9.5 \rightarrow 5.10$ transitions, the present experiments include a search for γ transitions corresponding to other decay modes of both resonances and an investigation of the properties of the γ transitions corresponding to the decay of the N^{14} 5.83-Mev and 5.10-Mev levels. The data obtained from these experiments were instrumental in the assignment of unique spin values to the 9.5-, 8.9-, 5.83-, and 5.10-Mev levels of N^{14}. Moreover, these data provided information useful in comparison of these levels with theoretical descriptions. In Sec. V the information obtained in the present investigation relating to these levels, as well as information obtained in previous investigations relating to these and other levels of N^{14} and C^{14}, is compared with shell-model systematics.

II. EXPERIMENTAL METHODS

A. Apparatus

The experiments described in this paper were carried out using two different elemental carbon targets, both of which were enriched to 70% in C^{13}. One target was cracked onto a 0.004-in. gold backing. The thickness of this target was 100 $\mu g/cm^2$ which corresponds to about 12 kev for 2-Mev protons. The other target was deposited on a 0.005-in. platinum backing.[9] The target profile was measured at the narrow ($\Gamma=100$ ev)[10] 1.76-Mev $C^{13}(p,\gamma)N^{14}$ resonance and the target was found to be nonuniform with an average thickness for 1.76-Mev protons of 45 kev ($\sim$60 kev for 1.47-Mev protons) and a maximum thickness of approximately 100 kev. All the experiments on the 2.1-Mev resonance were done with

[8] Broude, Green, Singh, and Willmott, Phil. Mag. **2**, 1006 (1957).

[9] Obtained from the Atomic Energy Research Establishment, Harwell, England.

[10] S. S. Hanna and L. Meyer-Schützmeister, Argonne National Laboratory Report ANL-5937 (unpublished).

the thinner target while the experiments on the 1.47-Mev resonance were carried out with both targets.

The protons were accelerated by the Brookhaven Research Van de Graaff accelerator. For some measurements the target was mounted on a tantalum strip, which was set at 45° to the beam inside a cylindrical glass target holder of uniform wall thickness. This arrangement was chosen in order to minimize γ-ray absorption corrections in angular distribution measurements. The beam current for this arrangement was limited to 1 μa. In order to use higher proton currents, the target was soldered with indium onto the bottom of a water-cooled brass cylinder. Proton currents up to 20 μa were used with this arrangement. To eliminate the γ-ray background from the $F^{19}(p,\alpha)O^{16}$ reaction, all surfaces struck by the proton beam were carefully cleaned by grinding with a carborundum wheel or boiling repeatedly in distilled water. In this manner the γ-ray background from the fluorine contamination was reduced to a negligible value.

The energy of the proton beam was determined and controlled by means of an electrostatic analyzer using the H_2^+ beam for regulation. With this analyzer the relative proton energy was reproducible to better than 1 kev. The analyzer was calibrated using the $Li^7(p,n)Be^7$ reaction for which the threshold energy was taken as 1.8814 ± 0.0011 Mev.[6]

Gamma rays with energies higher than 1 Mev were detected with a 3 by 3 in. NaI(Tl) crystal which was mounted on a Dumont 6363 photomultiplier. For the lower γ-ray energies a 2.5-in. long by 1.7-in. diameter NaI(Tl) crystal, mounted on a Dumont 6292 photomultiplier, was used. This same crystal served as the center unit in a three-crystal pair spectrometer, for which two 3-in. crystals were used to detect the annihilation radiation. The triple coincidence circuitry associated with the three-crystal pair spectrometer was essentially the same as described by Alburger and Toppel.[11] In all cases the γ-ray spectra were displayed on a RIDL 100-channel pulse-height analyzer.

B. Procedures

The studies of the γ rays from the decay of the N^{14} 8.9-Mev and 9.5-Mev levels consisted of relative intensity, angular distribution, anisotropy, and Doppler shift measurements.

The relative intensity measurements were carried out using the three-crystal pair spectrometer. For this purpose the relative efficiency of the pair spectrometer as a function of γ-ray energy was calculated for the 2.5-in. long center crystal from the cross section for pair production.[12]

The angular distributions of the γ rays, for which the full-energy-loss peaks were sufficiently resolved in NaI(Tl) single-crystal spectra, were determined from spectra recorded with the crystal placed at various angles to the beam at a distance of 12 cm from the target. At each angle the total charge of protons collected by the target was monitored with a current integrator, and also the reaction in the target was monitored with a second NaI(Tl) crystal viewing the target in a fixed position. In most cases the angular distribution of a given γ ray was obtained by taking the areas under the full-energy-loss peak from the spectra recorded at the various angles. The angular distribution data were corrected for the solid angle effect following the procedure outlined by Rose.[13]

Because of the complexity of the spectra observed at the two resonances, it was difficult, in most cases, to obtain significant angular distribution measurements from the single-crystal spectra. Hence the anisotropies of the principal γ rays were determined from three-crystal pair spectra for which the background and resolution conditions are significantly better than for single-crystal spectra.

The anisotropies were determined with the three-crystal pair spectrometer by recording the spectra at 0° and 90° to the bombarding beam. The anisotropy A of a particular γ ray is defined as $A=I(0°)/I(90°)-1$, where $I(\theta)$ is the intensity of the γ ray at an angle θ relative to the bombarding beam. The measured intensity depended very strongly on geometric factors which were difficult to reproduce and on the stability over extended periods of time of the window settings of the single-channel analyzers which accepted pulses from the escape annihilation quanta. Consequently, the 0° and 90° pair spectra were normalized with a line having a previously measured anisotropy.

The method of setting limits on the lifetime of a nuclear level by measuring the γ-ray Doppler shift due to the center-of-mass motion of the γ-emitting nuclei has been well described.[14,15] This method can be used to measure the mean lifetime τ of nuclear levels in the range $5\times10^{-12}\gtrsim\tau\gtrsim5\times10^{-14}$ sec. The essential feature of the measurement is to observe the slight shift in the observed pulse height of the full-energy-loss peak between observations made in forward and backward directions relative to the bombarding beam. When the measured shift of the peak is considered along with the stopping time ($\sim3\times10^{-13}$ sec) of the recoil nuclei, a limit, or limits, on the lifetime of the γ-emitting level can be set. The measurements of the Doppler shifts presented in this paper were carried out in a way which has been described previously.[16,17]

[11] D. E. Alburger and B. J. Toppel, Phys. Rev. **100**, 1357 (1955).
[12] See R. D. Bent and T. H. Kruse, Phys. Rev. **108**, 802 (1957) for details of the efficiency and resolution of a similar spectrometer.
[13] M. E. Rose, Phys. Rev. **91**, 610 (1953).
[14] R. G. Thomas and T. Lauritsen, Phys. Rev. **88**, 969 (1952).
[15] Devons, Manning, and Bunbury, Proc. Phys. Soc. (London) **A68**, 18 (1955).
[16] H. J. Rose and E. K. Warburton, Phil. Mag. **2**, 1468 (1957).
[17] E. K. Warburton and H. J. Rose, Phys. Rev. **109**, 1199 (1958).

III. EXPERIMENTAL RESULTS

A. Decay of the 9.50-Mev Level

The principal experimental results from observing the γ rays following the decay from the N^{14} 9.5-Mev level (formed by bombarding C^{13} with 2.1-Mev protons) consisted of relative intensity and anisotropy measurements of the principal γ rays obtained by means of a three-crystal pair spectrometer at 0° and 90° to the bombarding beam. Gamma rays at 0.73, 1.64, 3.68, 5.56, and 5.83 Mev not previously reported in the decay of the 9.5-Mev level were observed, and their decay modes were checked with standard $\gamma-\gamma$ coincidence techniques. The angular distribution about the beam of the 4.41- and 5.10-Mev γ rays corresponding to the $9.5\rightarrow 5.10$ and $5.10\rightarrow 0$ transitions, and a measured of the Doppler shift of the 5.10-Mev γ ray were also obtained.

In order to check the condition of the target and to observe the width and location of the 2.1-Mev resonance, an excitation function over the resonance was obtained as shown in Fig. 1. From observing this resonance curve it can be concluded that the resonances is located at a proton energy $E_p=2.112\pm 0.006$ Mev, which corresponds to a N^{14} level at 9.504 ± 0.006 Mev, and the resonance width is given by $\Gamma=44\pm 2$ kev in the laboratory frame of reference.

A (p,γ) excitation curve, yielding $E_p=2.10$-Mev and $\Gamma=45\pm 3$ kev, was previously obtained for this resoonance by Seagrave.[4] Zipoy *et al.*[2,3] reported a N^{14} level at 9.51 ± 0.02 Mev with $\Gamma\simeq 40$ kev from an analysis of the $C^{13}(p,p)C^{13}$ reaction. Since the width of the 2.11-Mev (p,γ) resonance is almost entirely due to the (p,p) reaction, it is apparent from the agreement in energy and width of the resonance observed by Zipoy *et al.*[2,3] with the one shown in Fig. 1 that the 2.1-Mev $C^{13}(p,p)C^{13}$ resonance and the 2.1-Mev $C^{13}(p,\gamma)N^{14}$ resonance correspond to the same N^{14} level.

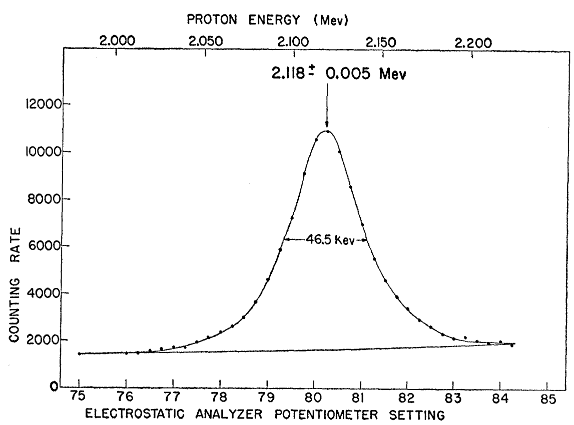

FIG. 1. The N^{14} 9.50-Mev level observed in the $C^{13}(p,\gamma)N^{14}$ reaction with a 12-kev thick, 70% enriched C^{13} target. The resonance curve was obtained with a single-channel analyzer set to count γ rays with energies between 3 and 5.5 Mev. The resonance was observed at a proton energy of 2.118 ± 0.005 Mev and the measured width was $\Gamma=46.5\pm 2$ kev. The actual energy location and width of the resonance, obtained by correcting the observed values for the target thickness, were $E_p=2.112\pm 0.006$ Mev and $\Gamma=44\pm 2$ kev. The N^{14} level position corresponding to $E_p=2.112\pm 0.006$ Mev is 9.504 ± 0.006 Mev. The background is mostly due to contaminants and the nonresonant 9.5-Mev γ ray.

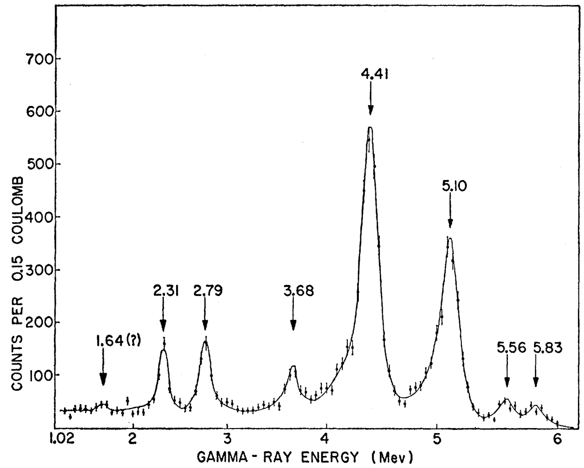

FIG. 2. Three-crystal pair spectrum of the γ rays from a 12-kev thick C^{13} target bombarded by 2.118-Mev protons. The center crystal of the spectrometer was placed at 0° to the beam and 6 cm from the target. The spectrum corresponds to an integrated charge of 0.15 coulomb and was taken with a 10-μa proton beam. Because of the low yield of the reaction no collimator was used, but the side crystals of the spectrometer were shielded against direct irradiation from the target. The γ-ray peaks are labeled by the computed energies of the transitions to which they are assigned.

Three-Crystal Pair Spectra

In Fig. 2 is shown one of several γ-ray spectra from the decay of the 9.50-Mev level observed at 0° to the beam with the three-crystal pair spectrometer. In order to determine the anisotropies of the γ rays and to search for γ rays which may have escaped detection at 0° because of a large negative anisotropy, other γ-ray spectra were recorded at 90° to the beam. One of the spectra recorded at 90° is shown in Fig. 3. From various pair spectra, single-crystal spectra, and coincidence measurements taken at various proton energies over the resonance it was observed that all of the γ rays identified in Figs. 2 and 3 were due to the 2.11-Mev resonance.

In Table I are listed the energies, assignments in the decay scheme, the relative intensities, and the anisotropies of the γ rays obtained from analysis of these three-crystal pair spectrometer runs. The spectra of Figs. 2 and 3 were decomposed into individual line shapes with the aid of comparison spectra from the Co^{60} 1.33-Mev γ ray, the ThC″ 2.62-Mev γ ray, and the 6.14-Mev γ ray from the $F^{19}(p,\alpha)O^{16*}(\gamma)O^{16}$ reaction. The background subtraction was aided by a comparison with pair spectra taken off-resonance. Corrections have been made for anisotropies as well as for pair-spectrometer efficiency in calculating the relative intensities of the γ rays. The correction for anisotropy was performed assuming all angular distribu-

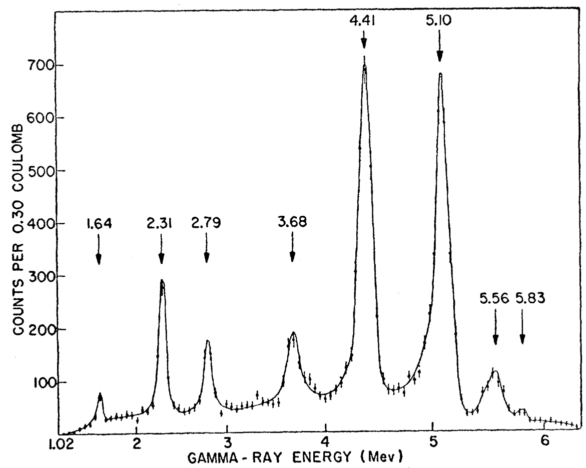

FIG. 3. Three-crystal pair spectrum of the γ rays from a 12-kev thick C^{13} target bombarded by 2.118-Mev protons. The center crystal of the spectrometer was placed at 90° to the beam and 6 cm from the target. The spectrum corresponds to an integrated charge of 0.30 coulomb and was taken with a 10-μa proton beam. Because of the low yield of the reaction no collimator was used, but the side crystals of the spectrometer were shielded against direct irradiation from the target. The γ-ray peaks are labeled by the computed energies of the transitions to which they are assigned.

tions were of the form $W(\theta)=1+A\cos^2\theta$, where A is the anisotropy. The errors listed for the intensities are principally due to counting statistics and uncertainties in background. The 2.79- and 5.83-Mev γ rays contain additional uncertainties due to the possibility of their distributions having terms in $\cos^4\theta$ (see Sec. IV). To obtain the anisotropies of the γ rays listed in Table I, the ratios $I(0°)/I(90°)$ were normalized using the single-crystal spectra measurement of the anisotropy of the 5.10-Mev γ ray as well as the isotropic 2.31-Mev γ-ray peak corresponding to the ground-state decay of the 0^+, N^{14} 2.31-Mev level.[6] The errors on the anisotropies listed in Table I contain the uncertainties in the relative intensities of the normalization peaks as well as the statistical errors of the measurements and the uncertainties in the background.

A separate search was made for the 9.5-Mev ground-state transition. A pair spectrum taken with low gain showed a 9.5-Mev γ ray with an intensity approximately 1/50 the intensity of the 4.41-Mev γ ray. A separate excitation curve was then obtained for the 2.11-Mev resonance with a window set between 8.5 and 10 Mev. The 9.5-Mev γ ray was found to be nonresonant with an upper limit to any possible resonant component of 10% so that a limit of less than 1/500 the intensity of the 4.41-Mev γ ray was set for the ground-state transition of the 9.50-Mev level. An upper limit of 1/50 the intensity of the 4.41-Mev γ ray was set for any other γ ray from this resonance with energy between 6 and 9 Mev.

In obtaining the excitation curve of Fig. 1, single-crystal spectra were recorded at each proton energy setting. Another excitation curve was obtained by extracting the area under the full-energy-loss peaks of the 4.41- and 5.10-Mev γ rays from these spectra. The excitation curve obtained in this manner agreed with the one of Fig. 2 with the background removed, and the relative cross section, which was checked between proton energies of 2.0 and 2.25 Mev, was in agreement with the simple dispersion formula within the experimental errors of the measurement. This measurement, together with the fact that the relative intensities of the various γ rays were independent of proton energy within the experimental errors of the measurement for $2.0<E_p<2.25$ Mev, served to set limits on the effects of interference with other levels yielding the same γ rays.

To confirm the decay modes of the 0.73-, 1.64-, 3.68-, 5.56-, and 5.83-Mev γ rays, which had not been observed previously at this resonance, coincidence measurements were carried out. By gating the coincidence circuit on the pulses due to the full-energy-loss peak of the 5.56-Mev γ ray in a 3-in. NaI(Tl) crystal and displaying the coincidence spectrum on the 100-channel analyzer, the 5.56-Mev γ ray was shown to be in coincidence with γ rays at 2.31 and 1.64 Mev and was assigned to the $9.50\rightarrow3.95$ transition since the N^{14} 3.95-Mev level is known[18] to decay 96% by cascade through the N^{14} 2.31-Mev level. In the same manner it was determined that the 5.83-Mev γ ray is in coincidence with a 3.68-Mev γ ray, and that the 5.10-Mev γ ray is in coincidence with γ rays at 4.41, 3.68, and 0.73 Mev, which is consistent with the previous assignment[6,17] of a 0.73-Mev γ ray to the $5.83\rightarrow5.10$ transition.

TABLE I. Decay scheme assignments, relative intensities, and anisotropies of γ rays from the decay of the N^{14} 9.50-Mev level formed by bombardment of a 12-kev thick, 70% enriched C^{13} target with 2.118-Mev protons.

γ-ray energy[a] (Mev)	Assignment[c]	Relative intensity	Anisotropy $[I(0°)/I(90°)-1]$
1.64[b]	$3.95\rightarrow2.31$	14 ± 6	-0.25 ± 0.4
2.31	$2.31\rightarrow0$	49 ± 3	-0.01 ± 0.10[e]
2.79	$5.10\rightarrow2.31$	31 ± 8	$+0.7\pm0.2$
3.68[b]	$9.50\rightarrow5.83$	21 ± 2	-0.17 ± 0.11
4.41	$9.50\rightarrow5.10$	100 ± 3[d]	$+0.70\pm0.10$
5.10	$5.10\rightarrow0$	80 ± 3	-0.09 ± 0.05[e]
5.56[b]	$9.50\rightarrow3.95$	8 ± 1	-0.43 ± 0.10
5.83[b]	$5.83\rightarrow0$	3 ± 1	$+2.3\pm1.0$
9.50	$9.50\rightarrow0$	<0.2	···

[a] The energies listed were computed from the known positions of the energy levels of N^{14} (see reference 6).
[b] Gamma rays previously unreported in the decay of the 9.50-Mev level.
[c] The assignments of the γ rays in N^{14} were made on the basis of previous assignments (reference 6), rough energy measurements ($\lesssim\pm80$ kev), $\gamma-\gamma$ coincidence measurements (see text), and the known positions of the N^{14} energy levels (reference 6).
[d] Normalization standard for relative intensities.
[e] Normalization standards for anisotropies. The 2.31-Mev γ ray is known to be isotropic (reference 6) and the value of the anisotropy of the 5.10-Mev γ ray was obtained in the single-crystal measurements (see text).

[18] Gove, Litherland, Almqvist, and Bromley, Phys. Rev. **103**, 835 (1956).

Angular Distributions

The full-energy-loss peaks of only the 5.10- and 4.41-Mev γ rays were sufficiently resolved in the NaI(Tl) single-crystal spectra so that a significant angular distribution measurement could be obtained. As can be seen in Fig. 4, only for the 5.10-Mev full-energy-loss peak is it fairly obvious how the separation of the peak from the background should be made. The angular distribution measurement obtained from the 4.41-Mev full-energy-loss peak is less exact since this peak has to be corrected for the presence of the 5.10-Mev one-quantum-escape peak and separated from a somewhat indefinite background.

The angular distribution of the 5.10-Mev γ ray is shown in Fig. 5(a). The curve shown is a least-squares fit to the function $W(\theta)=1+A\cos^2\theta$. After corrections have been made for solid angle and the presence of the 5.56- and 5.83-Mev γ rays, the least-squares fit gives $W(\theta)=1-(0.09\pm0.05)\cos^2\theta$. To determine the possible amounts of a $\cos^4\theta$ term in the distribution, a least-squares fit to the distribution $W(\theta)=1+A_2\cos^2\theta+A_4\cos^4\theta$ was carried out, yielding the result that $|A_4|<0.07$.

Figure 5(b) shows the data obtained on the 4.41-Mev γ-ray distribution. The flags on each point give error estimations which are almost entirely due to separation of the 4.41-Mev full-energy-loss peak from the one-quantum-escape peak of the 5.10-Mev γ ray. This separation was feasible only because the 5.10-Mev distribution is almost isotropic. A second method was used to estimate the angular distribution of the 4.41-Mev γ ray. In this method all counts between 2.9 and 5.3 Mev were summed to obtain an accurate estimate of the angular distribution for this part of the spectrum, and then corrections were made for the contributions of the 3.68- and 5.10-Mev γ rays. The two methods gave the same angular distribution, $W(\theta)=1+(0.70\pm0.15)\cos^2\theta$, for the 4.41-Mev γ ray, with $|A_4|<0.15$.

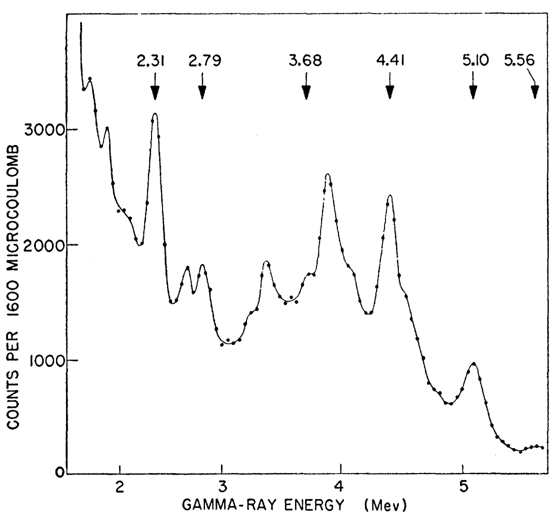

FIG. 4. Single-crystal spectrum of the γ rays from a 12-kev thick C^{13} target bombarded by 2.118-Mev protons. The spectrum was taken with a 3×3 in. NaI(Tl) crystal placed at 0° to the beam and 12 cm from the target. The full-energy-loss peaks of the γ rays are labeled by the computed energies of the transitions to which the γ rays are assigned.

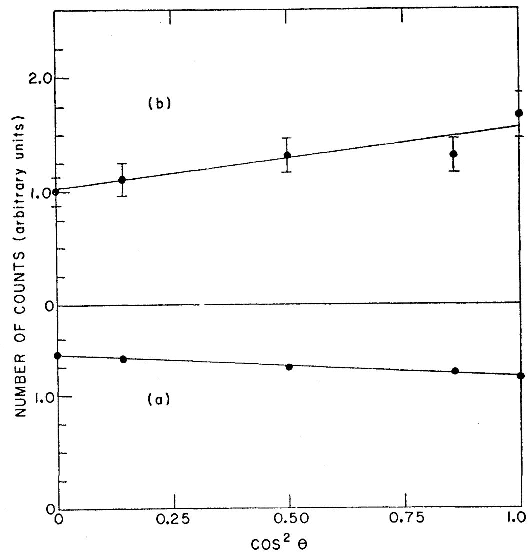

FIG. 5. Angular distributions of (a) the 5.10-Mev γ ray and (b) the 4.41-Mev γ ray observed following the bombardment of a 12-kev thick C^{13} target with 2.118-Mev protons. The solid curves are least-squares fits to the experimental data.

Doppler Shift Measurement

In order to obtain a lifetime estimate of the 5.10-Mev level, a measurement of the Doppler shift of the 5.10-Mev γ ray was carried out. The 5.10-Mev level is populated approximately 85% by the 4.41-Mev cascade from the 9.50-Mev level. The partial γ width obtained by Seagrave[4] for the 9.50-Mev level from the measurement of the absolute cross section of the $C^{13}(p,\gamma)N^{14}$ reaction at this resonance is $\Gamma_\gamma=25/(2J+1)$ ev. This width corresponds to a mean lifetime $\tau=3(2J+1)\times10^{-17}$ sec, where J is the spin of the 9.50-Mev level. Therefore the population of the 5.10-Mev level via the 4.41-Mev γ ray takes place in a time short compared to the stopping time ($\sim3\times10^{-13}$ sec) of the N^{14*} recoils and will not influence the Doppler shift of the 5.10-Mev γ ray.

The measurement was made using a 3-in. NaI(Tl) crystal which viewed the target alternately at 0° and 150° to the beam at a distance of 12 cm. The spectra were recorded by means of the 100-channel analyzer with the gain chosen so that the 5.10-Mev full-energy-loss peak appeared at channel 85. The spectrum was as shown in Fig. 4. A precision attenuator was used so that the 5.10-Mev γ ray could be displayed at about the same pulse height as the 1.33-Mev Co^{60} γ ray which was used as a reference for the measurement. The spectrum of the reference γ ray was recorded before and after each measurement of the 5.10-Mev γ ray. Altogether 20 measurements were obtained of the Doppler shift, yielding a result of $(0.07\pm0.07)\%$ for the measured Doppler shift of the 5.10-Mev line. The error given is the standard deviation. The expected full shift between 0° and 150° for a lifetime short compared to the stopping time is 0.72% after correcting for solid angle. Therefore this measurement shows that the mean life τ of the N^{14} 5.10-Mev level is long compared to the stopping time of the nitrogen recoils.

Since the thinner target (about 12-kev thick for 2-Mev protons) was used for this measurement the slowing down of the N^{14*} recoils takes place partially in the carbon target and partially in the gold backing. In the absence of reliable data on the slowing down of nitrogen in gold, a conservative limit of $\tau>3\times10^{-13}$ sec is set for the 5.10-Mev level from this measurement. This limit includes the uncertainty due to the 15% contribution to the 5.10-Mev γ ray arising from cascade via the 5.83-Mev level, i.e., the possible error introduced because the 0.73-Mev γ ray from the $5.83\rightarrow5.10$ transition may not have a lifetime which is negligibly short compared to the stopping time of the N^{14*} recoils.

B. Decay of the 8.90-Mev Level

Similar techniques as were employed in the study of the 9.50-Mev level proved useful for the investigation of the γ rays following the decay of the 8.90-Mev level (formed by bombarding C^{13} with 1.47-Mev protons). Three-crystal pair spectra obtained at 0° and 90° to the beam provided γ-ray relative intensities and anisotropies. Gamma rays at 1.89, 2.47, 3.80, 6.44, and 7.02 Mev not previously reported in the decay of the 8.90-Mev level were observed, and their decay modes were checked with standard $\gamma-\gamma$ coincidence techniques. Angular distribution measurements of the 0.73-, 3.08-, 5.10-, and 5.83-Mev γ rays, corresponding to the $5.83\rightarrow5.10$, $8.90\rightarrow5.83$, $5.10\rightarrow0$, and $5.83\rightarrow0$ γ transitions were carried out using a single scintillation crystal. A measurement of the Doppler shift of the 0.73-Mev γ ray yielded limits on the lifetime of the 5.83-Mev level.

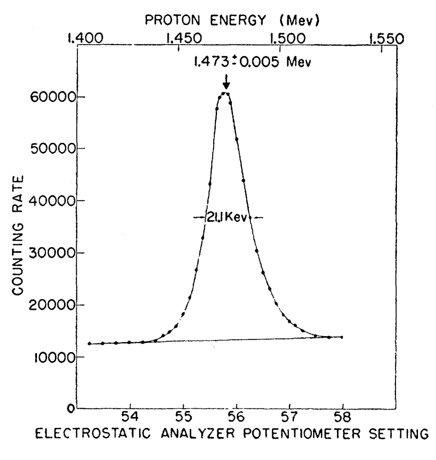

FIG. 6. The N^{14} 8.90-Mev level observed in the $C^{13}(p,\gamma)N^{14}$ reaction with a 14-kev thick, 70% enriched C^{13} target. The resonance curve was obtained with a single-channel analyzer set to count γ rays with energies between 2.8 and 6 Mev. The resonance was observed at a proton energy of 1.473 ± 0.005 Mev and the measured width was $\Gamma=21.1\pm2$ kev. The actual energy location and width of the resonance, obtained by correcting the observed values for the target thickness, are $E_p=1.466\pm0.006$ Mev and $\Gamma=16\pm2$ kev. The N^{14} level position corresponding to $E_p=1.466$ ±0.006 Mev is 8.903 ± 0.006 Mev. The background is mostly due to the γ transitions associated with the decay of the broad N^{14} 8.70-Mev level.

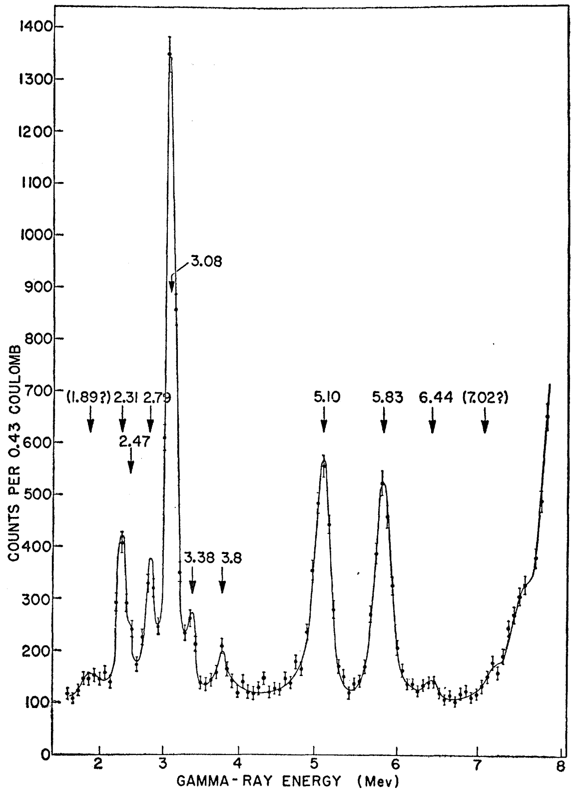

FIG. 7. Three-crystal pair spectrum of the γ rays from a 60-kev thick C^{13} target bombarded by 1.49-Mev protons. The center crystal of the spectrometer was placed at 0° to the beam and 13 cm from the target. The spectrum corresponds to an integrated charge of 0.43 coulomb and was taken with a 20-μa proton beam. The side crystals of the spectrometer were shielded against direct irradiation from the target by a 10.5 cm long conical lead collimator placed between the center crystal and the target. The γ-ray peaks are labeled by the computed energies of the transitions to which they are assigned.

The excitation function over the 1.47-Mev resonance was obtained as shown in Fig. 6. From this resonance curve it can be concluded that $E_p=1.466\pm0.006$ Mev, which corresponds to a N^{14} level at 8.903 ± 0.006 Mev, and $\Gamma=16\pm2$ kev in the laboratory frame of reference.

A (p,γ) excitation curve yielding $E_p=1.47$ Mev and $\Gamma=20$ kev was previously obtained for this resonance.[4,5] This level has also been observed from the $C^{13}(p,p)C^{13}$ reaction[1]; however, the proton scattering data has not been analyzed to obtain the energy position or the width of the resonance. The background under the resonance curve of Fig. 6 is for the most part due to the board ($\Gamma = 500$ kev)[4] $C^{13}(p,\gamma)N^{14}$ 1.25-Mev resonance, which corresponds to the 0^-, N^{14} 8.70-Mev level.[6] A cursory investigation of the γ transitions associated with this background was made as an aid in the interpretation of the 8.90-Mev level decay.

Three-Crystal Pair Spectra

Two of the pair spectra observed with the three-crystal spectrometer at 0° and 90° to the incoming proton beam are shown in Figs. 7 and 8, and the assignments in the decay scheme, relative intensities, and anisotropies of the γ rays obtained from these spectra are given in Table II.

The data of Table II were obtained from the pair spectra in the same manner as described previously for the 2.11-Mev resonance with the exception that the 0° and 90° spectra were normalized with the isotropic 2.31-Mev γ ray alone, and the relative intensities were corrected for the contribution of the background by subtracting from the spectra of Figs. 7 and 8 other spectra taken under similar conditions but off-resonance ($E_p = 1.40$-Mev). All the labeled peaks in Figs. 7 and 8 with the exception of the ones at 3.2 and 3.38 Mev, which are not resonant at a proton energy of 1.47 Mev, arise at least partially from γ rays associated with the 1.47-Mev resonance. The 3.2-Mev γ ray has a large negative anisotropy so that its presence is apparent in the 90° spectrum (Fig. 8)—by filling in the valley between the 3.08- and 3.38-Mev peaks—but not in the 0° spectrum (Fig. 7). The 3.8- and 2.31-Mev peaks contain appreciable contributions from the background. The other background peaks

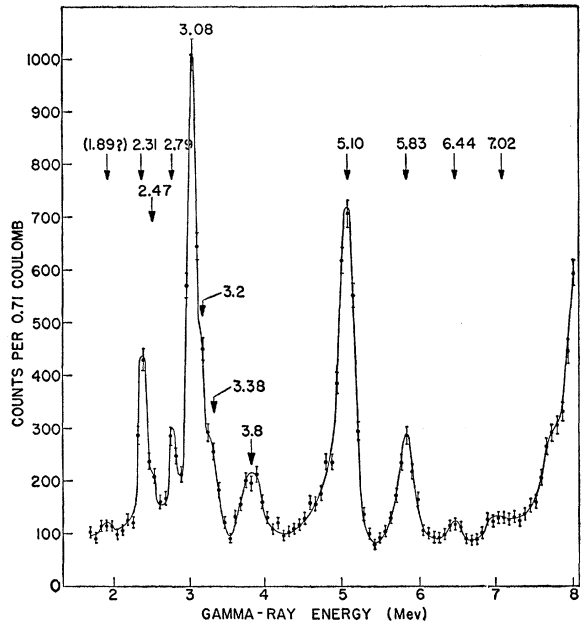

FIG. 8. Three-crystal pair spectrum of the γ rays from a 60-kev thick C^{13} target bombarded by 1.49-Mev protons. The center crystal of the spectrometer was placed at 90° to the proton beam and 13 cm from the target. The spectrum corresponds to an integrated charge of 0.71 coulomb and was taken with a 20-μa proton beam. The side crystals of the spectrometer were shielded against direct irradiation from the target by a 10.5 cm long conical lead collimator placed between the center crystal and the target. The γ-ray peaks are labeled by the computed energies of the transitions to which they are assigned.

are unresolved from, and small compared to, the 5.10- and 5.83-Mev peaks. None of the decay modes of the 8.90-Mev level (see Table II) were the same as those observed for the background to the 1.47-Mev resonance. Only the data relating to the 1.47-Mev resonance are listed in Table II.

The increase of the intensity above 7 Mev in Figs. 7 and 8 is caused by the 8.9-Mev γ ray which corresponds to the ground-state decay of the broad 8.70-Mev level. A search was made for the ground-state transition of the 8.90-Mev level using the 14-Kev thick C^{13} target. A single-channel analyzer window was set to count γ rays between 7.5 and 9.5 Mev as the proton bombarding energy was varied over the 1.47-Mev resonance. In this way an upper limit of 5% was set for any component of the 8.9-Mev γ ray associated with the 8.90-Mev level. The intensity ratio of the 8.9-Mev γ ray to the 3.08-Mev γ ray was determined to be approximately 1 : 2 at $E_p = 1.47$ Mev from a three-crystal pair spectrum taken with lower gain. Hence an upper limit of 1/40 of the intensity of the 3.08-Mev γ ray was set for the ground-state branch from the 8.90-Mev level.

To confirm the decay modes of the γ rays at 1.89, 2.47, 3.80, 6.44, and 7.02 Mev, which had not been previously observed at this resonance, $\gamma-\gamma$ coincidence measurements were carried out. It was thus shown that the 1.89-Mev γ ray was in cascade with the

TABLE II. Decay scheme assignments, relative intensities, and anisotropies of γ rays from the decay of the N^{14} 8.90-Mev level formed by bombardment of a 60-kev thick, 70% enriched C^{13} target with 1.49-Mev protons.

γ-ray energy[a] (Mev)	Assignment[c]	Relative intensity	Anisotropy $[I(0°)/I(90°)-1]$
1.89[b]	$8.90 \rightarrow 7.02$	...	...
2.31	$2.31 \rightarrow 0$	29 ± 9[d]	$+0.01 \pm 0.12$[f]
2.47[b]	$8.90 \rightarrow 6.44$	6 ± 4	...
2.79	$5.10 \rightarrow 2.31$	17 ± 5	$+0.7$ $+0.4$
3.08	$8.90 \rightarrow 5.83$	100 ± 13[d,e]	$+0.6 \pm 0.2$[d]
3.80[b]	$8.90 \rightarrow 5.10$	5.5 ± 2.5[d]	-0.3 ± 0.3[d]
5.10	$5.10 \rightarrow 0$	40 ± 6	-0.09 ± 0.12
5.83	$5.83 \rightarrow 0$	17 ± 3	$+1.87 \pm 0.42$
6.44[b]	$6.44 \rightarrow 0$	2 ± 1	$+0.1 \pm 0.5$
7.02[b]	$7.02 \rightarrow 0$	1.4 ± 0.8	-0.35 ± 0.4
8.90	$8.90 \rightarrow 0$	<2.5	...

[a] The energies listed were computed from the known positions of the energy levels of N^{14} (see reference 6).
[b] Gamma rays previously unreported in the decay of the 8.90-Mev level.
[c] The assignments of the γ rays in N^{14} were made on the basis of previous assignments (reference 6), rough energy measurements ($\lesssim \pm 80$ kev), $\gamma-\gamma$ coincidence measurements (see text), and the known positions of the N^{14} energy levels (reference 6).
[d] The uncertainties in these measurements contain a large contribution from the uncertainty in the subtraction of the off-resonance ($E_p = 1.40$ Mev) spectra.
[e] Normalization standard for relative intensities.
[f] Normalization standard for anisotropies.

TABLE III. Decay scheme assignments, relative intensities, and anisotropies of γ rays following proton bombardment of a 65-kev thick, 70% enriched C^{13} target with 1.40-Mev protons.

γ-ray energy[a] (Mev)	Assignment[c]	Relative intensity	Anisotropy $[I(0°)/I(90°)-1]$
2.31	$N^{14}(2.31 \to 0)$	19±3	0.0±0.1[e]
3.11	$N^{14}(8.80 \to 5.69)$	11±2	−0.95±0.1
3.38	$N^{14}(5.69 \to 2.31)$	7±2	−0.1±0.3
3.89	$N^{14}(8.80 \to 4.91)$	6±2	−0.5±0.3
4.83	$N^{14}(8.80 \to 3.95)$	7±2	...[f]
4.91	$N^{14}(4.91 \to 0)$		...[f]
5.69	$N^{14}(5.69 \to 0)$	2±1	+0.1±0.4
6.14	$F^{19}(p,\alpha)O^{16*}$ $(6.14 \to 0)O^{16}$	7±0.5	−0.15±0.1[e]
8.80[b]	$N^{14}(8.80 \to 0)$	100±20[d]	...

[a] The energies listed were computed from the known positions of the energy levels of N^{14} (see reference 6).
[b] This energy was calculated from the incident proton energy and from the target profile determined at the 1.47-Mev resonance.
[c] The assignments of the γ rays in N^{14} were made on the basis of previous assignments (reference 6), rough energy measurements ($\lesssim\pm 80$ kev), coincidence measurements (see text), and the known positions of the N^{14} energy levels (reference 6).
[d] Normalization standard for relative intensities.
[e] Normalization standard for anisotropies. The anisotropy of the O^{16} 6.14-Mev γ ray was previously measured at the $E_p=1.38$-Mev resonance in $F^{19}(p,\alpha)O^{16*}(\gamma)O^{16}$ to be $A=0.14\pm0.03$ [J. E. Saunders, Phil. Mag. **44**, 1302 (1953)].
[f] The 4.83- and 4.91-Mev γ-ray peaks were unresolved.

7.02-Mev γ ray, as was the 2.47-Mev γ ray with the 6.44-Mev γ ray and the 3.80-Mev γ ray with the 5.10-Mev γ ray. Furthermore, it was shown that the 0.73-Mev transition is in cascade with the 5.10-Mev transition, which implies that the 0.73-Mev γ ray is from a transition between the 5.83- and the 5.10-Mev levels, in agreement with previous assignments[6,17] and the present investigation of the 9.50-Mev level decay.

Gamma-Ray Background at the 1.47-Mev Resonance

The γ radiation background to the 1.47-Mev resonance was investigated in order to separate the contributions of this background from the γ radiation arising from the N^{14} 8.90-Mev level and to search for possible interference between γ transitions associated with this background and the γ transitions associated with the 8.90-Mev level. The principal results consisted of pair spectra taken with the thick C^{13} target at a proton energy of 1.40 Mev. The results obtained in this investigation which give information relating to the γ decay of the 0^-, N^{14} 8.70-Mev level will be discussed in Sec. IVC.

Three-crystal pair spectra were recorded at 0° and 90° to the beam at $E_p=1.40$ Mev, each with an integrated charge of 0.4 coulomb. The decay scheme assignments, relative intensities, and anisotropies of the observed γ rays derived from the pair spectra and from other measurements are listed in Table III. The γ-ray peak at 6.14 Mev was assumed to arise from the $F^{19}(p,\alpha)O^{16*}(\gamma)O^{16}$ reaction, which has a strong resonance at $E_p=1.38$ Mev.[6] The 6.14-Mev peak was not observed at $E_p=1.47$ Mev, where the $F^{19}(p,\alpha)O^{16*}(\gamma)O^{16}$ reaction has no resonance. From the excitation curve obtained for the thick target at the 1.47-Mev resonance, the average excitation energy in N^{14} for 1.40-Mev protons incident on the thick target was calculated to be 8.80±0.02 Mev. The suggested assignments to the N^{14} cascades given in Table III were checked by $\gamma-\gamma$ coincidence measurements, and also by measurements of the γ-ray energies obtained from both single-crystal and coincidence spectra.

The 3.11- and 5.69-Mev γ rays were shown to be in cascade by displaying the spectrum in coincidence with each in turn. The energy of the 3.11-Mev γ ray was measured in single-crystal spectra to be 3.11±0.03 Mev. This measurement rules out the possibility that this γ ray contains an appreciable contribution from the $8.80 \to 5.83$ transition. Assignment to the $C^{12}(p,\gamma)N^{13}$ reaction, for which the ground-state transition would have an energy of 3.20 Mev for the target and proton energy used, is also ruled out by this energy measurement. A ground-state transition following the $C^{12}(p,\gamma)N^{13}$ reaction at $E_p=1.40$ Mev was not observed in the bombardment of a natural carbon target, thus further excluding the assignment of the 3.11-Mev γ ray to the $C^{12}(p,\gamma)N^{13}$ reaction.

By displaying the spectrum in coincidence with the pulses from a 400-kev wide single-channel analyzer window centered at 4.8 Mev, the 4.83-Mev γ ray was found to be in coincidence with γ rays at 1.64 and 2.31 Mev. In the same manner the 3.89-Mev γ ray was shown to be in cascade with a γ ray having an energy of 4.96±0.07 Mev. From the upper limit set on the intensity of the 2.79-Mev γ ray ($5.10 \to 2.31$ transition), which was not observed in the spectrum in coincidence with the 3.89-Mev γ ray, an upper limit of 1 : 2 was set to the ratio of the intensities of the γ rays feeding the 5.10- and 4.91-Mev levels. The statistics and resolution of the three-crystal pair spectra were not sufficient to separate the 3.70- and 3.89-Mev γ rays corresponding to the $8.80 \to 5.10$ and $8.80 \to 4.91$ transitions, or the 4.83-, 4.91-, and 5.10-Mev γ rays corresponding to the $8.80 \to 3.95$, $4.91 \to 0$, and $5.10 \to 0$ transitions. Therefore, it is possible that the 3.89-Mev peak and the unresolved 4.83- and 4.91-Mev peaks listed in Table III contain a contribution from the $8.80 \to 5.10$ and $5.10 \to 0$ transitions, with the $8.80 \to 5.10$ transition one-half as intense as the $8.80 \to 4.91$ transition.

Single-crystal spectra, as well as coincidence spectra similar to those described above, were taken at various proton energies between 1.40 and 1.54 Mev. All the γ rays assigned to N^{14} in Table III were observed on both sides of the 1.47-Mev resonance, and a rough check showed that the intensities of these γ rays were the same within a factor of two at $E_p=1.40$ and 1.54 Mev. No large fluctuations in the intensities of the γ rays listed in Table III were apparent between these two energies. The background correction to the pair spectra obtained at the 1.47-Mev resonance was carried out assuming that the background spectra was the same at $E_p=1.40$ and 1.47 Mev with the exception of the increase in the energy of the primary γ rays, such as the 3.11-Mev γ ray corresponding to the $8.80\rightarrow 5.69$ transition. The background correction was made by subtracting the $E_p=1.40$-Mev 0° and 90° spectra, properly normalized, from the $E_p=1.47$-Mev 0° and 90° spectra (Figs. 7 and 8), respectively, to obtain the data of Table II.

In none of the measurements described above were any γ-ray transitions, except the ground-state transition of the 0^+, N^{14} 2.31-Mev level, observed arising from the background to the 1.47-Mev resonance which were the same as any of the γ-ray transitions assigned to the 8.90-Mev level. These measurements, then, give the principal justification for treating the 1.47-Mev resonance as well-isolated (i.e., being able to neglect the effects of interference with overlapping levels) in the analysis of the experimental γ-ray anisotropies. The possibility of a weak transition to the 5.10-Mev level from the nonresonant background of the 1.47-Mev resonance cannot be excluded by the present experiments, however, and is indicated by the results of Broude *et al.*[8] (see Sec. IVC). For this reason the analysis of the data from the investigations of the 1.47- and 2.11-Mev resonances was carried out in a way which was independent of the results obtained for the $8.90\rightarrow 5.10$ transition.

Angular Distributions

A single-crystal spectrum of the γ rays from the decay of the 8.90-Mev level as observed with a 3-in. NaI(Tl) crystal is shown in Fig. 9. As can be seen from this spectrum, none of the γ-ray lines can be separated from overlapping peaks or from the background with great accuracy. Nevertheless, it was possible to obtain rough measurements of the angular distributions of the 3.08-, 5.10-, and 5.83-Mev γ rays and a measurement of the anisotropy of the 0.73-Mev γ ray. The angular distributions were obtained from 18 spectra taken at 8 different angles between 0° and 150° to the beam using a 3-in. NaI(Tl) crystal.

The angular distribution of the 3.08-Mev γ ray was obtained from spectra recorded by the 100-channel analyzer with a bias of 2.7 Mev, as shown in the insert of Fig. 9. Two different angular distribution functions were obtained from these spectra by taking the area under the 3.08-Mev full-energy-loss peak assuming the two limits for the background shown by B_1 and B_2 in the insert of Fig. 9. Both angular distribution functions were of the form $W(\theta)=1+A\cos^2\theta$ within the experimental error, i.e., $|A_4|<0.10$. However, the anisotropies obtained from the two background estimates, which were assumed to be limiting values, were $A=+0.8$ for B_1 and $A=+0.3$ for B_2. This large difference reflects the sensitivity of anisotropy measurements of highly anisotropic γ rays to the method of background subtraction.

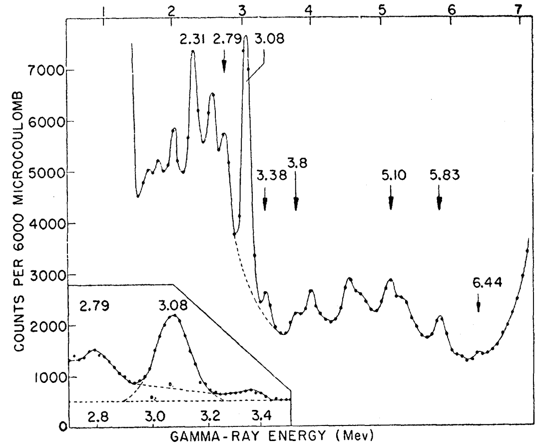

FIG. 9. Single-crystal spectrum of the γ rays from a 60-kev thick C^{13} target, bombarded by 1.49-Mev protons. The spectrum was taken with a 3×3 in. NaI(Tl) crystal placed at 0° to the beam and 12 cm from the target. The full-energy-loss peaks of the γ rays are labeled by the computed energies of the transitions to which the γ rays are assigned. The insert shows the full-energy-loss peak of the 3.08-Mev γ ray recorded by the 100-channel analyzer with a bias of 2.7 Mev.

The angular distribution functions of the 5.10- and 5.83-Mev γ rays were obtained from the areas under their respective full-energy-loss peaks (see Fig. 9) Again the accuracy of the measurement was determined by the extraction of the peak areas from the spectra. A least-squares fit of the data for the 5.83-Mev γ ray gave $W(\theta)=1+(0.7\pm0.3)\cos^2\theta+(1.0\pm0.5)\cos^4\theta$[19] with $A=1.75\pm0.40$. A least-squares fit of the data for the 5.10-Mev γ ray gave $W(\theta)=1+(0.07\pm0.12)\cos^2\theta$ with a limit on a possible $\cos^4\theta$ term of $|A_4|<0.10$.

The anisotropy of the 0.73-Mev γ ray, which arises from the $5.83\rightarrow 5.10$ transition, was also determined from single-crystal spectra using the 60-Kev thick C^{13} target. The anisotropy was obtained from six spectra recorded using a 2.5 by 1.7 in. NaI(Tl) crystal placed alternately at 0° and 90° to the beam. The 0.73-Mev full-energy-loss peak was well resolved and superimposed on a uniform background so that a relatively accurate determination of the anisotropy could be made. The average value obtained was $A=-0.25\pm0.06$.

Doppler Shift Measurement

In order to investigate the lifetime of the 5.83-Mev level, a measurement of the Doppler shift of the 0.73-Mev γ-ray cascade between the 5.83- and 5.10-Mev levels was made. The 5.83-Mev level is populated at this resonance by the 3.08-Mev γ-ray cascade from the 8.90-Mev level. The partial width Γ_γ of the 8.90-Mev level is $2.9/(2J+1)$ ev[4] which corresponds to a mean

[19] The existence of a $\cos^4\theta$ term in the angular distribution of the $5.83\rightarrow 0$ transition was found to be practically independent of the background assumed in extracting the 5.83-Mev full-energy-loss peak from the spectra. Therefore, in spite of the large uncertainty in its value, the existence of a positive A_4 in the angular distribution of the 5.83-Mev γ ray was established without any question.

life $\tau = 2.3(2J+1)\times 10^{-16}$ sec, where J is the spin of the 8.90-Mev level. Since this mean life is negligibly short compared to the stopping time of the N^{14*} recoils ($\sim 3\times 10^{-13}$ sec), the Doppler shift of the 0.73-Mev γ ray is unaffected by the lifetime of the 8.90-Mev level.

The detector, a 2.5 by 1.7 in. NaI(Tl) crystal, viewed the target at a distance of 6 cm at 0° to the beam, and at a backward angle of 120°. The thick target was used. The 0.73-Mev full-energy-loss peak, from which the Doppler shift was obtained, was well-resolved on a flat, uniform background.

Three independent sets of data were obtained using three different bias and gain settings in conjunction with the 100-channel analyzer. In the first set, eight determinations of the Doppler shift yielded a shift of $(0.42\pm 0.09)\%$, the second set of six determinations gave $(0.35\pm 0.05)\%$, while the third set of six determinations gave $(0.43\pm 0.16)\%$. The errors given are the standard deviations. A weighted average of these three results yields $(0.39\pm 0.05)\%$ for the Doppler shift of the 0.73-Mev γ ray. The Doppler shift calculated from the kinematics assuming a lifetime short compared to the stopping time of the N^{14*} nuclei, is 0.58% including the solid angle correction. The Doppler shift measurement, then, indicates that the mean lifetime of the 5.83-Mev level is of the order of the stopping time of the N^{14*} recoils, and limits can be placed on the mean lifetime from an estimate of the N^{14*} stopping time.

The stopping time of nitrogen in carbon was estimated by extrapolating stopping power data[20] and also by using the curves of range *versus* velocity of nitrogen ions in nitrogen given by Blackett and Lees.[21] From these data it was found that the range *versus* velocity curve in the region of interest was quite linear with the constant α from the expression $R=\alpha v$ given by $\alpha = (4.0\pm 1.5)\times 10^{-13}$ sec. The mean lifetime τ was obtained from the expression[15]

$$\frac{\text{Measured Doppler shift}}{\text{Calc. full Doppler shift}} = \frac{\alpha/\tau}{1+\alpha/\tau},$$

which gave $6.5\times 10^{-13} > \tau > 5\times 10^{-14}$ sec, where the limits correspond to two standard deviations from the measured Doppler shift (i.e., 0.29% and 0.49%, respectively). When combined with the branching ratio of the 5.83-Mev level obtained from the relative intensities of Tables I and II, the lifetime limits on the 5.83-Mev level gives $5\times 10^{-12} > \tau > 2.5\times 10^{-13}$ sec for the $5.83 \rightarrow 0$ transition and $7.7\times 10^{-13} > \tau > 6\times 10^{-14}$ sec for the $5.83 \rightarrow 5.10$ transition.

TABLE IV. Partial gamma widths and Weisskopf matrix elements for the primary γ rays observed at the 1.47- and 2.11-Mev resonances.

Transition	$\omega\Gamma_\gamma{}^f$ [a]	$\omega\|M\|^2$ [b] $E1$	$M1$	$E2$	$M2$	$\Delta(\%)$ [c]
1.47-Mev resonance						
$8.90 \rightarrow 5.10$	0.040	0.0011	0.034	12	390	45
$8.90 \rightarrow 5.83$	0.65	0.035	1.06	580	18 000	3.3
$8.90 \rightarrow 6.44$	0.022	0.0023	0.072	63	1970	33
$8.90 \rightarrow 7.02$	0.010	0.0024	0.072	106	3360	57
2.11-Mev resonance						
$9.50 \rightarrow 3.95$	0.37	0.006	0.102	17	540	17
$9.50 \rightarrow 5.10$	4.8	0.088	2.66	710	22 600	3.8
$9.50 \rightarrow 5.83$	1.0	0.031	0.95	366	11 600	12

[a] The statistical factor ω is $(2J+1)/4$, where J is the spin of the resonance level. The total partial γ width Γ_γ from reference 4 has been apportioned into the fractional partial γ widths $\Gamma_\gamma{}^f$ for each decay mode from the relative intensities of Tables I and II.
[b] The Weisskopf matrix element $|M|^2$ for a particular multipolarity is defined as the ratio of the experimental $\Gamma_\gamma{}^f$ to the Weisskopf estimate for the radiative width of that multipolarity.
[c] The uncertainty Δ, which is the percentage uncertainty in both $\omega\Gamma_\gamma{}^f$ and $\omega|M|^2$, was obtained from the relative intensity measurements (Tables I and II), and does not include the uncertainty assigned (reference 4) to the Γ_γ.

C. Summary of Experimental Results

In the next section (Sec. IVA) the measurements reported in Secs. IIIA and B, together with the absolute $C^{13}(p,\gamma)N^{14}$ cross-section data of Seagrave[4] and the assignments for the 8.90- and 9.50-Mev levels of $J^\pi = 1^-$, 2^-, or 3^- consistent with the proton scattering analysis of Milne[1] and Zipoy *et al.*,[2,3] will be used to assign spin values to the N^{14} 9.50-, 8.90-, 5.83-, and 5.10-Mev levels. In Sec. IVB the information obtainable from the experimental data (past and present) which relates to the multipole mixtures of some of the observed γ rays will be discussed. For the convenience of discussions which will follow in the remainder of this paper, the absolute cross section data of Seagrave[4] is combined here in tabular form (Table IV) with the relative intensity data of Tables I and II to give parameters useful in the assignment of multipolarities to the γ-ray transitions.

From the absolute cross-section measurements on the $C^{13}(p,\gamma)N^{14}$ reaction at the 2.11-Mev and 1.47-Mev resonances, Seagrave[4] obtained partial widths Γ_γ for γ decay of $6.15/\omega$ and $0.72/\omega$, respectively, where ω is a statistical factor given by $(2J+1)/4$. In Table IV these partial widths are apportioned among the various decay modes given in Tables I and II for the 2.11- and 1.47-Mev resonances. In Table IV, $\omega\Gamma_\gamma{}^f$ is the fraction of $\omega\Gamma_\gamma$ due to a particular transition. The $\omega\Gamma_\gamma{}^f$ were obtained from the relative intensities given in Tables I and II. The matrix elements $|M|^2$ for dipole and quadrupole transitions can be obtained for a particular value of J from the $\omega|M|^2$ listed in Table IV. The matrix element $|M|^2$ is defined as the ratio of $\Gamma_\gamma{}^f$ to the Weisskopf[22] single-particle estimate of the radiative width of the transition. The single-particle estimates were calculated from formulas given by Wilkinson.[23]

[20] S. K. Allison and S. D. Warshaw, Revs. Modern Phys. **25**, 779 (1953).
[21] P. M. S. Blackett and D. S. Lees, Proc. Roy. Soc. (London) **A134**, 658 (1932).
[22] V. F. Weisskopf, Phys. Rev. **83**, 1073 (1951).
[23] D. H. Wilkinson, Phil. Mag. **1**, 127 (1956), and *Proceedings of the Rehovoth Conference on Nuclear Structure*, edited by H. J. Lipkin (North-Holland Publishing Company, Amsterdam, 1958), Session IV, p. 175.

The γ-ray angular distribution and lifetime data, which have not been included in Tables I and II, are collected in Table V. For comparison, anisotropies obtained from the three-crystal pair spectrometer measurements (see Tables I and II) and from previous investigations are also shown. The anisotropies obtained from the single-crystal measurements and the pair spectrometer measurements are seen to be in good agreement. The anisotropy given by Woodbury *et al.*[5] for the $9.50 \to 5.10$ transition is in fair agreement with the present result. The anisotropy measurement of Woodbury *et al.* was obtained from single-crystal spectra, and most probably would have been influenced by the presence of the $9.5 \to 5.83$ transition which has a negative anisotropy (see Table I). A correction for the presence of this transition, of which they were unaware, would bring their anisotropy measurement of the $9.50 \to 5.10$ transition into closer agreement with the anisotropy obtained in the present work. The anisotropy given by Woodbury *et al.*[5] for the $8.90 \to 5.83$ transition, also obtained from single-crystal spectra, is in poor agreement with the present result. Again a correction for the presence of the transitions corresponding to other decay modes (see Tables II and III) would bring their anisotropy measurement into closer agreement with the anisotropy obtained in the present work. Moreover, as discussed previously, the value of the anisotropy obtained for the $8.90 \to 5.83$ transition from single-crystal spectra is quite sensitive to the assumed background used to extract the 3.08-Mev full-energy-loss peak.

Most of the conclusions which will be drawn in the remainder of this paper will depend on the assumption that the 1.47-Mev and 2.11-Mev resonances are well isolated in the sense that for a particular γ-ray transition the contribution from other levels or from a nonresonant background, is negligible. The intensity data presented in Tables I and II are relatively insensitive to contributions from overlapping resonances since the contributions to the total intensity (i.e., integrated over the sphere) of a particular γ ray from different resonances add incoherently. However, the contributions from different resonances to a particular γ-ray intensity $I(\theta)$ at an angle θ to the proton beam add coherently so that the anisotropy of the γ transition is dependent on the relative amplitudes of the interfering resonances and is quite sensitive to the contributions of overlapping resonances (see Devons and Goldfarb[24] for a discussion of interference in p,γ reactions). The measurements designed to determine the extent of any possible interference effects were (1) the determination of the excitation function over the resonance for each particular decay mode in order to set limits on the nonresonant contribution to each γ ray as previously discussed for the 2.11-Mev resonance, (2) a check of the symmetry of the angular distributions about 90° for the more important γ rays, since a lack of symmetry about 90° is a sensitive indication of interference with a level of opposite parity, (3) a determination of the anisotropy of the 3.08-Mev γ ray of the 8.90-Mev resonance with both the thin (14 kev thick) and thick (60 kev thick) targets to investigate the energy dependence of the anisotropy. In none of these measurements were any effects attributable to interference observed within the experimental errors.

These measurements do not constitute an exhaustive examination of the possibility of interference for the resonances involved; however, they indicate limits on the possible effects of interference to a sufficient extent so that conclusive spin assignments can be obtained from an analysis carried out under the assumption of well-isolated resonances.

TABLE V. Summary of the single-crystal angular distribution and lifetime measurements.

Transition	$W(\theta)$[a]	A (singles)[b]	A (pair)[c]	A (previous)[d]	A (average)[e]	Lifetime limits
1.47-Mev resonance						
$8.90 \to 5.83$	$\|A_4\|<0.10$	$+0.3<A<0.8$	$+0.6\ \pm0.2$	$+0.25\pm0.10$	$+0.6\ \pm0.2$	···
$5.83 \to 0$	$A_2=0.7\pm0.3$, $A_4=1\pm0.5$	$+1.75\pm0.40$	$+1.87\pm0.42$	···	$+1.8\ \pm0.4$	$5\times10^{-12}>\tau>2.5\times10^{-13}$ sec
$5.83 \to 5.10$	···	-0.25 ± 0.06	···	···	-0.25 ± 0.06	$7.7\times10^{-13}>\tau>6\times10^{-14}$ sec
$5.10 \to 0$	$\|A_4\|<0.10$	$+0.07\pm0.12$	-0.09 ± 0.12	···	-0.01 ± 0.12	···
2.11-Mev resonance						
$9.50 \to 5.10$	$\|A_4\|<0.15$	$+0.70\pm0.15$	$+0.70\pm0.10$	$+0.48\pm0.15$	$+0.70\pm0.10$	···
$5.10 \to 0$	$\|A_4\|<0.07$	-0.09 ± 0.05	f	···	-0.09 ± 0.05	$\tau>3\times10^{-13}$ sec (for 5.10-Mev level)

[a] $W(\theta)=1+A_2\cos^2\theta+A_4\cos^4\theta$.
[b] The anisotropy A is $I(0°)/I(90°)-1$, so that $A=A_2+A_4$.
[c] From Tables I and II.
[d] See reference 5.
[e] Average of A (singles) and A (pair).
[f] The anisotropy obtained for this γ ray in the singles spectra was used for normalization of the 0° and 90° pair spectra.

[24] S. Devons and L. J. B. Goldfarb, *Handbuch der Physik* (Springer-Verlag, Berlin, 1957), Vol. 42, p. 362.

IV. ANALYSIS OF RESULTS

A. Spin Assignments

Using the experimental data which was presented in the previous section together with the requirement that the 8.90- and 9.50-Mev levels have $J^\pi=1^-$, 2^-, or 3^- (see Sec. I), it is possible to give conclusive spin assignments to the 5.10-, 5.83-, 8.90-, and 9.50-Mev levels in N^{14}. It is also possible to give a tentative spin assignment to the N^{14} 7.02-Mev level.

The available empirical evidence[23] for light nuclei indicates that the Weisskopf lifetime estimate for $E2$ transitions is a good lower limit if collective contributions to the radiative transition rate are taken into account. There is little available evidence for $M2$ transitions in light nuclei; however, what evidence[23] there is, and the evidence from heavier nuclei,[25] indicates that the Weisskopf estimate is as good a lower limit for $M2$ transitions as for $E2$ transitions. For the purpose of drawing conclusions as to the maximum contribution of quadrupole radiation to the γ transitions observed in N^{14}, an upper limit of 25 (i.e., collective enhancement by all the protons outside the 1s shell) is set for the matrix element $|M|^2$ for quadrupole radiation. With this conservative limit as a guide, it is apparent that the $8.90\rightarrow5.83$, $9.50\rightarrow5.83$, and $9.50\rightarrow5.10$ transitions are at least partially dipole in character since the smallest value of $|M|^2$ obtained from Table IV for these three transitions is $|M|^2=209$ (the $9.50\rightarrow5.83$ $E2$ transition with $J=3$ for the 9.50-Mev level). The $9.50\rightarrow3.95$ transition can also be established as at least partially dipole by using the spin-parity assignment to the N^{14} 3.95-Mev level. The most probable assignment to the 3.95-Mev level given in the compilation of Ajzenberg and Lauritsen[6] is $J^\pi=1^+$. The evidence for this assignment and later work verifying it is discussed in the next paragraph.

Stripping analysis of the $C^{13}(d,n)N^{14}$ reaction indicates[26] $J^\pi=0^+$, 1^+, or 2^+ for the N^{14} 3.95-Mev level. The parity assignment has been verified by a study of the linear polarization of the $3.95\rightarrow2.31$ transition.[27] The 3.95-Mev level decays 96% by cascade through the 0^+ 2.31-Mev level and 4% by a direct transition to the $J^\pi=1^+$, N^{14} ground state.[18] Therefore $J^\pi=0^+$ is eliminated and 1^+ is favored over 2^+ for the 3.95-Mev level. The N^{14} 8.62-Mev level, for which $J^\pi=0^+$,[6] has been observed[5,28] to decay to the 3.95-Mev level. If the decay scheme established by Wilkinson and Bloom[28] for the 8.62-Mev level is combined with the partial width Γ_γ given by Seagrave[4] for the 8.62-Mev level, a radiative width of 1.26 ev is obtained for the $8.62\rightarrow3.95$ transition. This width corresponds to an $E2$ matrix element of $|M|^2=140$ which is clearly impossible. Therefore, the $8.62\rightarrow3.95$ transition must be predominantly $M1$ and the 3.95-Mev level has $J^\pi=1^+$.

With the 3.95-Mev level established as $J^\pi=1^+$, the transition to it from the odd-parity 9.50-Mev level must be $E1$, $M2$, etc. The $M2$ matrix elements for the $9.50\rightarrow3.95$ transition are (see Table IV) 720, 430, and 310 for spin assignments to the 9.50-Mev level of 1, 2, and 3, respectively. It is apparent, then, that the $9.50\rightarrow3.95$ transition is predominantly $E1$. The $J^\pi=1^+$ assignment to the N^{14} 3.95-Mev level together with the dipole character of the $9.50\rightarrow3.95$ transition eliminates the possible assignment of $J^\pi=3^-$ for the 9.50-Mev level. Consequently, the dipole character of the $9.50\rightarrow5.10$ and $9.50\rightarrow5.83$ transitions limits the possible spin values of the 5.10- and 5.83-Mev levels to $J\leqslant3$. The anisotropies of the $5.83\rightarrow0$, $5.83\rightarrow5.10$, and $5.10\rightarrow2.31$ transitions (see Tables I, II, and V) eliminate the possibility of $J=0$ for the 5.83- and 5.10-Mev levels.

The angular distributions of the γ rays about the beam were calculated for the possible reaction and level parameters from the theoretical formulas given by Biedenharn *et al.*[29] and by Devons and Goldfarb.[24] In what follows, $A(\gamma_i)$ is used to denote the theoretical anisotropy of the ith γ ray in a γ-ray cascade originating at the resonance level. The anisotropies $A(\gamma_1)$ for dipole transitions between the resonance level with spin J_1 and a level with spin J_2 are listed in Table VI. For pure dipole radiation the angular distribution function must have the form $W_i(\theta)=1+A(\gamma_i)\cos^2\theta$, so that the anisotropy completely defines $W_i(\theta)$. The anisotropies of Table VI were calculated for d-wave protons and for the allowed values of the channel spin S, which are $S=1$ for $J_1=1$ or 3, and $S=0$ or 1 for $J_1=2$. For $J_1=2$, the anisotropies are given in terms of the fractional contribution of channel spin $S=0$,

$$x=|A(0)|^2/[|A(1)|^2+|A(0)|^2],$$

after the notation of Biedenharn *et al.*[29]

It is seen from Table VI that for pure dipole radiation, if $J_1=J_2$ the anisotropy is positive, while if $J_1\neq J_2$ the anisotropy is negative. The anisotropies of the observed

TABLE VI. Anisotropies computed for pure dipole radiation following d-wave proton capture by C^{13}.

J_1	J_2	$A(\gamma_1)$
1	0	-0.60
1	1	$+0.43$
1	2	-0.07
2	1	$-(3+3x)/(9+x)$
2	2	$+(3+3x)/(7-x)$
2	3	$-(3+3x)/(29+x)$
3	2	-0.44
3	3	$+0.82$
3	4	-0.20

[25] M. Goldhaber and A. W. Sunyar, *Beta- and Gamma-Ray Spectroscopy*, edited by K. Siegbahn (North-Holland Publishing Company, Amsterdam, 1955), Chap. XVI (II), p. 453.
[26] R. E. Benenson, Phys. Rev. **90**, 420 (1953).
[27] A. E. Litherland and H. E. Gove, Bull. Am. Phys. Soc. Ser. II, **3**, 200 (1958).
[28] D. H. Wilkinson and S. D. Bloom, Phil. Mag. **2**, 63 (1957).
[29] Biedenharn, Arfken, and Rose, Phys. Rev. **83**, 586 (1951).

γ rays are subject to perturbations from the values of Table VI due to the interference of the quadrupole and dipole components of the transition. The effects of this interference were investigated by calculating the angular distribution functions of the various possible transitions in terms of the relative intensities of quadrupole and dipole radiation. From these angular distribution functions, one of which is given in Sec. IVB, it was apparent that, within the limits set on the intensity of the quadrupole radiation by the matrix elements of Table IV (again using the limit $|M|^2<25$ for quadrupole radiation), the signs of the anisotropies of the $8.90\rightarrow5.83$, $9.50\rightarrow5.10$, and $9.50\rightarrow5.83$ transitions could not be changed by the quadrupole contribution to the transitions. The $8.90\rightarrow5.83$ transition was observed (see Table II) to have a positive anisotropy while the $9.50\rightarrow5.10$ and $9.50\rightarrow5.83$ transitions were observed (see Table I) to have positive and negative anisotropies, respectively. Therefore as long as the 8.90-Mev level does not have $J^\pi=1^-$, in which case the possible interference between s-wave and d-wave formation of the level must be considered,[30] the 8.90-Mev level has the same spin as the 5.83-Mev level. Likewise, if the 9.50-Mev level has $J^\pi=2^-$ (3^- having been excluded by the dipole character of the $9.50\rightarrow3.95$ transition) it has the same spin as the 5.10-Mev level, and its spin differs by one unit from that of the 5.83-Mev level.

In order to obtain conclusive spin assignments for the 9.50-, 8.90-, 5.83, and 5.10-Mev levels, it is necessary to use the anisotropies measured for the second and/or third γ rays in the γ-ray cascades assigned in Tables I and II. One means of obtaining the spin assignments of these levels is from the anisotropies of the γ rays in the cascade

$$8.90(J_1)\xrightarrow{\gamma_1}5.83(J_2)\xrightarrow{\gamma_2}5.10(J_3)\xrightarrow{\gamma_3}2.31(J_4).$$

The anisotropies calculated for these γ rays, assuming d-wave formation of the 1.47-Mev resonance and pure dipole radiation for γ_1 and γ_2, are given in Table VII. These anisotropies were calculated for all combinations of the spin assignments to the 8.90-, 5.83-, and 5.10-Mev levels consistent with the arguments presented above and using the known zero spin of the 2.31-Mev level. The multipole order of γ_3 is, of course, determined by the spin J_3 of the 5.10-Mev level.

As in the case of the anisotropies $A(\gamma_1)$ of the first γ rays in the γ-ray cascades, the anisotropy $A(\gamma_2)$ of the $5.83\rightarrow5.10$ transition is subject to an uncertainty due to the possible quadrupole component in the transition. A limit on the intensity of the quadrupole radiation was set, in this case, by the lifetime measurement (Table V) of the 5.83-Mev level. Using the Weisskopf estimates for quadrupole radiation with $E_\gamma=0.73$ Mev ($\tau=9.1\times10^{-10}$ sec for $E2$ and $\tau=2.9\times10^{-8}$ sec for $M2$), the limit $|M|^2<25$ for quadrupole radiation, and the upper limit on the lifetime of the $5.83\rightarrow5.10$ transition ($\tau<7.7\times10^{-13}$ sec), it is apparent that the $5.83\rightarrow5.10$ transition is predominantly dipole, and it was found that the allowable contribution of quadrupole radiation was not enough to change the sign of any of the anisotropies $A(\gamma_2)$ calculated for this transition.[31] Since the quadrupole mixture in γ_i will affect the anisotropies of the successive γ rays γ_{i+1}, γ_{i+2}, etc., through the intensity ratio of the quadrupole and dipole components and not through the amplitude ratio, the quadrupole component of γ_1 will have negligible affect on $A(\gamma_2)$ and $A(\gamma_3)$ and the quadrupole component of γ_2 will have negligible effect on $A(\gamma_3)$.

In the case of $J_1=1$ the angular distribution functions of the various cascade γ rays must be of the form $W_i(\theta)=1+a_2P_2(\cos\theta)\equiv1+A\cos^2\theta$. If the resonance level with $J_1=1$ is formed by a mixture of s-wave and d-wave protons, then the constant a_2, calculated for pure d-wave formation, will be multiplied by[24]

$$(1\mp2\sqrt{2}\delta_s)/(1+\delta_s^2),$$

where δ_s is the ratio of the amplitude of s-wave formation to d-wave formation, including the relative phase factor, for formation of a N^{14} 1^- level from $C^{13}+p$. It is apparent then that any mixing of s-wave formation in the case of $J_1=1$ will affect all the $A(\gamma_i)$ in the cascade in the same sense. That is, the magnitude of each anisotropy in the cascade will be changed in the same direction and if the sign of one is changed the sign of all of them will be changed.

The measured anisotropies (Table II) of the 3.08-Mev γ ray (γ_1), 0.73-Mev γ ray (γ_2), and 2.79-Mev γ ray (γ_3) were $+0.60\pm0.20$, -0.25 ± 0.06, and $+0.7\pm0.4$, respectively. Keeping in mind the limits on the effects of quadrupole radiation mixing in γ_1 and γ_2 and the functional behavior of the effects of mixing of s-wave and d-wave formation of the 8.90-Mev level for $J_1=1$, it is seen from Table VII that the combination of

TABLE VII. The anisotropies of the first (γ_1), second (γ_2), and third (γ_3) γ rays in a γ-ray cascade following capture of d-wave protons by C^{13} and assuming pure dipole radiation for γ_1 and γ_2.

J_1	J_2	J_3	J_4	$A(\gamma_1)$	$A(\gamma_2)$	$A(\gamma_3)$
1	1	1	0	$+0.43$	-0.18	-0.18
1	1	2	0	$+0.43$	$+0.04$	-0.18
1	2	1	0	-0.07	-0.24	-0.24
2	2	1	0	$+(3+3x)/(7-x)$	$-(3+3x)/(17+x)$	$-(3+3x)/(17+x)$
2	2	2	0	$+(3+3x)/(7-x)$	$+(1+3x)/(15-x)$	$+(7x-1)/(3+3x)$
3	3	2	0	$+0.82$	-0.34	$+0.65$

[30] A $J^\pi=1^-$ resonance in N^{14} can be formed from $C^{13}+p$ by s-wave or d-wave protons, a $J^\pi=2^-$ resonance can only be formed by d-wave protons. A $J^\pi=3^-$ resonance in N^{14} can be formed from $C^{13}+p$ by d-wave or g-wave protons. The effects of g-wave formation were investigated by calculating the possible interference between d waves and g waves with the maximum g-wave amplitude allowed by the barrier penetrability and the Wigner limit to the reduced width. It was found that the effects of g-wave formation were entirely negligible.

[31] See Sec. IVB for a typical example of the effects of quadrupole mixing on the anisotropy of the 0.73-Mev γ ray.

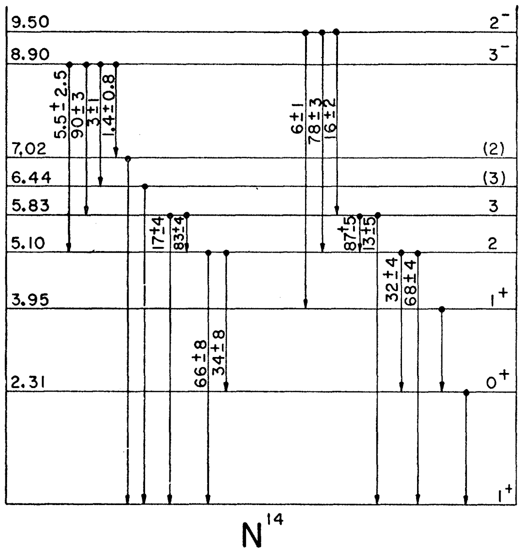

FIG. 10. The decay schemes of the N^{14} 8.90- and 9.50-Mev levels as determined in the present work. Only the levels involved in the decay of the 8.90- and 9.50-Mev levels are shown. The spin assignments of the 9.50-, 8.90-, 7.02-, 5.83-, and 5.10-Mev levels are discussed in the text. The other spin and parity assignments are from previous work.

spins $J_1=3$, $J_2=3$, and $J_3=2$ is compatible with the measured anisotropies for γ_1, γ_2, and γ_3, while all the other possible combinations of spins give anisotropies in great disagreement with the measured anisotropies. Therefore, the 8.90- and 5.83-Mev levels are assigned $J=3$, while the 9.50- and 5.10-Mev levels are assigned $J=2$.

Other arguments can be advanced from the data of Sec. III to give independent evidence for the spin assignments of these four levels. For instance the appearance of a term in $\cos^4\theta$ (see Table V) in the angular distribution of the $5.83 \rightarrow 0$ transition observed at the 1.47-Mev resonance establishes $J\neq 1$ for the 8.90- and 5.83-Mev levels independent of other evidence. The $\cos^4\theta$ term in the $5.83 \rightarrow 0$ transition also eliminates the possibility that the 1.47-Mev resonance could be formed by p-wave protons. However, for the 9.50-Mev level, p-wave formation with $J^\pi=2^+$ cannot be definitely ruled out on the basis of the present experiments alone. Therefore, the spin assignments made above are not independent of the proton scattering experiments[1–3] which show that the 9.50-Mev level, as well as the 8.90-Mev level, is formed predominantly by d-wave protons.

From Table IV it is seen that the $8.90 \rightarrow 6.44$ and $8.90 \rightarrow 7.02$ transitions most likely have dipole components so that the relative intensity measurements give probable spins of $J=2$, 3 or 4 to the 6.44- and 7.02-Mev levels. The anisotropies of the 2.47- and 1.89-Mev γ rays corresponding to the $8.90 \rightarrow 6.44$ and $8.90 \rightarrow 7.02$ transitions were not measured because of the relatively weak intensity of these γ rays and the small pair production cross section for $E_\gamma < 3$ Mev. The anisotropy measurement of the 6.44-Mev γ ray corresponding to the 6.44-Mev level ground-state transition was too inaccurate to allow any significant conclusions to be drawn. The anisotropy of the 7.02-Mev γ ray, corresponding to the 7.02-Mev level decay to the 1^+, N^{14} ground state, was measured to be -0.35 ± 0.40. The calculated anisotropies $A(\gamma_2)$ for d-wave formation of a $J_1=3^-$ resonance level are -0.43, $+0.68$, and $+1.62$ for $J_2=2$, 3, and 4, respectively, if γ_1 and γ_2 are assumed to have the lowest allowed multipolarities. Therefore, insofar as the $8.90 \rightarrow 7.02$ transition is dipole and the $7.02 \rightarrow 0$ transition proceeds by the lowest allowed multipolarity, the 7.02-Mev level most likely has $J=2$, so that a tentative assignment of $J=2$ is given to the 7.02-Mev level. This result is in agreement with the stripping analysis[26] of the $C^{13}(d,n)N^{14}$ reaction which gave a slight indication that the N^{14} 7.02-Mev level has $J^\pi \leqslant 2^+$.

In Fig. 10 is shown the decay schemes of the 8.90- and 9.50-Mev levels. The branching ratios were calculated from the relative intensities given in Tables I and II. Other transitions with branching ratios comparable to those given in Fig. 10 may exist for either resonance. For instance, a transition from the 9.50-Mev level to the N^{14} 5.69-Mev level, with a branching ratio approximately one-half or less that of the $9.50 \rightarrow 3.95$ transition, would probably have been undetected. The branching ratios for the N^{14} 5.10- and 5.83-Mev levels were previously obtained by Woodbury *et al.*[5] The present results for the 5.10-Mev level are in agreement with the results of Woodbury *et al.*, while the present results for the 5.83-Mev level are not. The disagreement for the branching ratios of the 5.83-Mev level may be due to the large anisotropies of the $8.90 \rightarrow 5.83$, $5.83 \rightarrow 0$, and $5.83 \rightarrow 5.10$ transitions, for which Woodbury *et al.* did not make a correction.

The spin assignments discussed above were made by comparison with the signs, but not the measured values, of the anisotropies of the observed γ rays. This method was used so that the conclusions would be as independent as possible of complicating effects. In Table VIII a comparison is made of all the measured anisotropies (obtained from Tables I, II, and V) with the anisotropies calculated from the spin assignments shown in Fig. 10. The theoretical anisotropies were calculated assuming all the transitions proceed by the lowest possible multipolarity. From a comparison of the experimental and theoretical anisotropies for the $9.50 \rightarrow 5.10$, $9.50 \rightarrow 5.83$, and $5.10 \rightarrow 2.31$ (from the 9.50-Mev level) transitions, x, the fractional contribution of channel spin $S=0$ in the formation of the 9.50-Mev level, was determined to be $x=0.56\pm0.14$.

The experimental anisotropies of the $8.90 \rightarrow 5.83$, $5.83 \rightarrow 5.10$, and $5.10 \rightarrow 0$ transitions from the 8.90-Mev level and the $5.10 \rightarrow 0$ transition from the 9.50-Mev level are seen, from Table VIII, to be in poor agreement with the theoretical anisotropies; thus implying the mixing of higher multipolarities in these transitions.[32] In the next subsection the experimental anisotropies and angular distributions obtained for these transitions will be compared to the angular distribution functions calculated assuming mixing of the lowest and next-to-lowest allowed multipole orders.

B. Gamma-Ray Transitions with Mixed Multipolarities

The theoretical angular distribution functions for a transition involving both the lowest (L) and the next-to-lowest ($L+1$) allowed multipolarities were calculated from formulas given by Devons and Goldfarb.[24] The functions are given in terms of δ, where δ^2 may be interpreted as

$$\delta^2=\Gamma_\gamma^f(L+1)/\Gamma_\gamma^f(L),$$
with
$$\Gamma_\gamma^f(L+1)+\Gamma_\gamma^f(L)=\Gamma_\gamma^f, \qquad (1)$$

so that $\Gamma_\gamma^f(L)$ is the contribution of the Lth multipole order to the radiative width Γ_γ^f of the transition. The phase of δ is the same as that given by Devons and Goldfarb. The functions were calculated using the spin assignments and cascades given in Fig. 10 with d-wave formation of the 8.90- and 9.50-Mev levels. In the case of the $5.10\rightarrow 0$ transition the angular distribution functions given are weighted averages of two functions since, for both resonances, the 5.10-Mev level is fed by both the resonance level and the 5.83-Mev level.[33]

In Figs. 11 through 13 are shown the anisotropies calculated as a function of δ for the $8.90\rightarrow 5.83$, $5.83\rightarrow 5.10$ and $5.83\rightarrow 0$ transitions of the 1.47-Mev resonance, while in Figs. 14(a) and (b) are shown the mixing curves of the $5.10\rightarrow 0$ transition of the 2.11- and 1.47-Mev resonances, respectively. The theoretical angular distribution functions and the ranges of δ corresponding to the anisotropy measurements are given in the figure captions.

The experimental anisotropies of the 8.90 ($J=3$) $\rightarrow$ 5.83 ($J=3$) and 5.83 ($J=3$) $\rightarrow$ 5.10 ($J=2$) transitions (see Figs. 11 and 12, respectively) almost overlap with the theoretical anisotropies ($A=+0.82$ and -0.34, respectively) for pure dipole radiation, so that there could very well be no mixing of quadrupole radiation in these transitions. The mixing curves for these transitions are given for the following reasons: (1) To illustrate the statement made in the last subsection that the sign of the anisotropies of these transitions could not be changed from that calculated for pure dipole radiation within the allowable limits on the matrix elements for quadrupole radiation. (2) To illustrate the most probable sign of δ, since the relative phase of the dipole and quadrupole amplitudes might be of future interest for comparison with model-dependent analysis of the N^{14} levels. (3) To give the limits on δ, and thus an estimation of the limits on the matrix elements for quadrupole radiation.

The Weisskopf matrix elements calculated from the Γ_γ^f of the 8.90 ($J=3$) $\rightarrow$ 5.83 ($J=3$) transition assuming pure $E2$ and $M2$ radiation are (see Table III) 330 and 10 000. From Eq. (1) it is seen that $\delta^2/(1+\delta^2)$ is the fraction of the transition intensity which is assigned to the quadrupole radiation if it is assumed that there is no contribution from multipole orders with $L\geqslant 3$. Therefore, the limit on the quadrupole matrix element $|M|^2<25$, corresponds to $|\delta|<0.27$ [i.e., $\delta^2/(1+\delta^2)<25/330$] for $M1$-$E2$ mixing and $|\delta|<0.05$ for $E1$-$M2$ mixing in the $8.90\rightarrow 5.83$ transition. From Fig. 11, then, it is seen that the possible values of δ are given by $0\lesssim\delta<0.2$ corresponding to $|M|^2\lesssim 13$ for $E2$ radiation and $|M|^2\lesssim 400$ for $M2$ radiation.[34]

The upper limit to the mean lifetime τ of the 5.83 $\rightarrow$ 5.10 transition was calculated to be (see Table V) 7.7×10^{-13} sec, while the Weissiopf estimates for this transition are 9.1×10^{-10} sec for $E2$ and 2.9×10^{-8} sec for $M2$. From these values and the limit on the quadrupole matrix element $|M|^2<25$, a limit $|\delta|\lesssim 0.15$ is calculated for the 5.83 ($J=3$) $\rightarrow$ 5.10 ($J=2$) transition. Therefore, observation of Fig. 12 shows that the requirement that $|M|^2<25$ for quadrupole radiation

TABLE VIII. Comparison of the experimental and theoretical anisotropies corresponding to the decay schemes of Fig. 10.

Transition	A (experimental)[a]	A (theoretical)[b]
1.47-Mev resonance		
$8.90\rightarrow 7.02$	...	-0.44
$8.90\rightarrow 6.44$	...	$+0.82$
$8.90\rightarrow 5.83$	$+0.60\pm0.20$	$+0.82$
$8.90\rightarrow 5.10$	$-0.3\ \pm0.3$	-0.44
$7.02\rightarrow 0$	-0.35 ± 0.4	-0.44
$6.44\rightarrow 0$	$+0.1\ \pm0.5$	$+0.68$
$5.83\rightarrow 0$	$+1.80\pm0.40$	$+0.68$
$5.83\rightarrow 5.10$	-0.25 ± 0.06	-0.34
$5.10\rightarrow 0$[c]	-0.01 ± 0.12	-0.34
$5.10\rightarrow 2.31$[c]	$+0.7\pm0.4$	$+0.65$
$2.31\rightarrow 0$	0.0 ± 0.12	0.0
2.11-Mev resonance		
$9.50\rightarrow 5.83$	-0.17 ± 0.11	$-(3+3x)/(29+x)$
$9.50\rightarrow 5.10$	$+0.70\pm0.10$	$+(3+3x)/(7-x)$
$9.50\rightarrow 3.95$	-0.43 ± 0.10	$-(3+3x)/(9+x)$
$5.83\rightarrow 0$	$+2.3\pm1.0$	$(434-49x)/(840-273x)$
$5.10\rightarrow 0$[c]	-0.09 ± 0.05	$-(3+3x)/(17+x)$
$5.10\rightarrow 2.31$[c]	$+0.70\pm0.20$	$+(7x-1)/(3+3x)$
$3.95\rightarrow 2.31$	-0.25 ± 0.4	$-(3+3x)/(9+x)$
$2.31\rightarrow 0$	-0.01 ± 0.12	0.0

[a] See Tables I, II, and V.
[b] Calculated from references 24 and 29.
[c] A (theoretical) was calculated for the major cascade, the error due to neglecting the $8.90\rightarrow 5.10$ cascade, in the case of the 1.47-Mev resonance, and the $9.50\rightarrow 5.83\rightarrow 5.10$ cascade, in the case of the 2.11-Mev resonance, is within the experimental uncertainties.

[32] Because the 3^- 8.90-Mev level is formed by channel spin $S=1$ and the 0^- 8.70-Mev level is formed by channel spin $S=0$, no interference between these two levels is possible, so that multipole mixing is the most likely explanation for the difference of the theoretical and experimental anisotropies for the 1.47-Mev resonance as well as for the 2.11-Mev resonance.

[33] For both resonances the angular distribution function for the $5.10\rightarrow 0$ transition was almost entirely determined by the more intense cascade to the 5.10-Mev level, and the error introduced by the uncertainty in the branching ratios was negligible.

[34] Since these limits are intended as rough guides the uncertainties in the $|M|^2$ of Table IV are neglected.

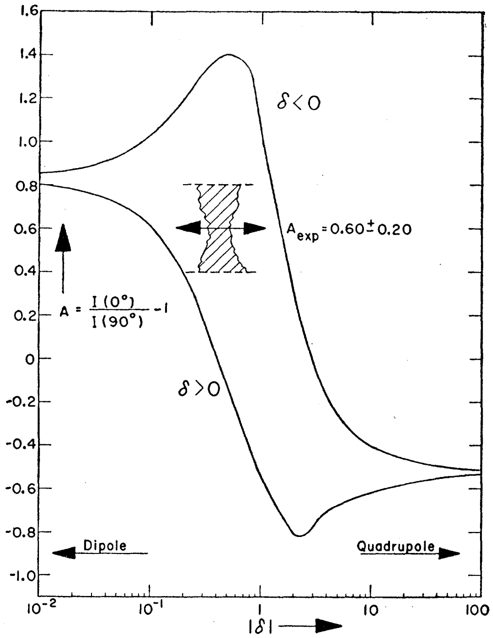

FIG. 11. The anisotropy of the 8.90 $(J=3)\rightarrow 5.83(J=3)$ γ transition following the formation of the 3^-, N^{14} 8.90-Mev level by d-wave protons. The transition is assumed to be a mixture of dipole and quadrupole radiation with an intensity ratio $\delta^2=\Gamma_\gamma{}^f(2)/\Gamma_\gamma{}^f(1)$. This figure shows as a function of $|\delta|$ the anisotropy A of the angular distribution of the γ transition relative to the proton beam. Each one of the two curves corresponds to a definite sign of δ. The two curves were calculated from the theoretical angular distribution function: $W(\theta)=1+a_2P_2(\cos\theta)+a_4P_4(\cos\theta)$, where $a_2=0.43(1\pm2\delta-0.524\delta^2)/(1+\delta^2)$; $a_4=-0.30\delta^2/(1+\delta^2)$. The formulas for computing $W(\theta)$ can be found in reference 24. The measured anisotropy is also shown. The measured anisotropy limits the possible values of δ to $0\lesssim\delta\leqslant0.2$ and $-1.2>\delta>-1.9$.

rules out the positive values of δ allowed by the meassured anisotropy, and the limits on δ are $0\gtrsim\delta>-0.1$, corresponding to $|M|^2\lesssim12$ for $E2$ and $|M|^2\lesssim380$ for $M2$.

The mixing curve for the 5.83 $(J=3)\rightarrow 0$ $(J=1)$ transition of the 1.47-Mev resonance (Fig. 13) indicates a mixture of quadrupole and octupole radiation with an unambiguous choice of the sign of δ. The limits on δ corresponding to the measured anisotropy are $-0.4>\delta>-4$.[35] The limits on the mean lifetime of the $5.83\rightarrow0$ transition calculated from the measurement of the Doppler shift of the 0.73-Mev γ ray were 5×10^{-12} sec $>\tau>2.5\times10^{-13}$ sec. From the upper limit to the mean lifetime of the transition and the lower limit on δ^2, a lower limit can be estimated for the matrix element of the octupole radiation component of the $5.83\rightarrow0$ transition. The Weisskopf estimates for the mean lifetime of this transition are 2.8×10^{-14}, 8.8×10^{-13}, 2×10^{-10}, and 3×10^{-9} sec for $E2$, $M2$, $E3$, and $M3$, respectively. The experimental lifetime is consistent with the quadrupole component being either $E2$ or $M2$, while the Weisskopf matrix elements for $E3$ and $M3$ corresponding to $\tau=5\times10^{-12}$ sec and $\delta=-0.4$ are $|M|^2=5.5$ for $E3$ and $|M|^2=140$ for $M3$; therefore, the limits on $|M|^2$, corresponding to $\tau<5\times10^{-12}$ sec and $\delta>-0.4$, are $|M|^2\gtrsim5$ for $E3$ and $|M|^2\gtrsim140$ for $M3$. The N^{14} ground state has positive parity so that, insofar as an $E3$ matrix element greater than 5 is more likely than an $M3$ matrix element greater than 140, the 5.83-Mev level most likely has negative parity.

The values of δ allowed by the anisotropy measurements of the $5.10\rightarrow0$ transitions at the 1.47- and 2.11-Mev resonances are in good agreement [see Figs. 14(a) and (b)]. Since $E1$, $M1$, $E2$, and $M2$ radiation are all consistent with the limit $(\tau>3\times10^{-13}$ sec) set on the mean lifetime of the 5.10-Mev level, no choice can be made between the two signs of δ allowed by the anisotropy measurements from this limit. However, an indication that the range of δ correspond-

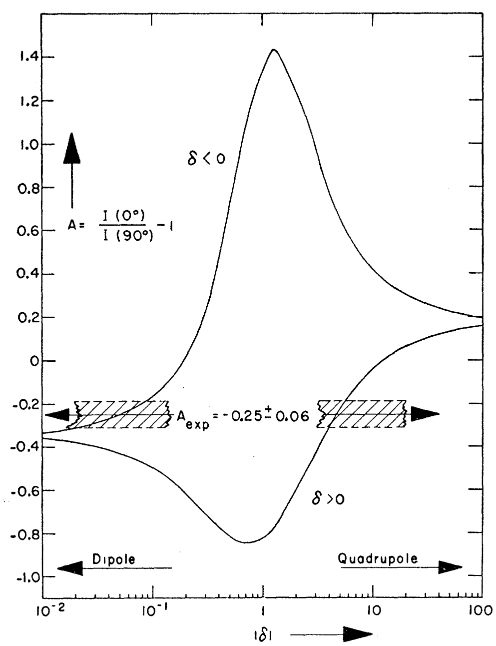

FIG. 12. The anisotropy of the 5.83 $(J=3)\rightarrow5.10$ $(J=2)$ γ transition following the formation of the 3^-, N^{14} 8.90-Mev level by d-wave protons. The transition is assumed to be a mixture of dipole and quadrupole radiation with an intensity ratio $\delta^2=\Gamma_\gamma{}^f(2)/\Gamma_\gamma{}^f(1)$. This figure shows as a function of $|\delta|$ the anisotropy A of the angular distribution of the γ transition relative to the proton beam. Each one of the two curves corresponds to a definite sign of δ. The two curves were calculated from the theoretical angular distribution function: $W(\theta)=1+a_2P_2(\cos\theta)+a_4P_4(\cos\theta)$, where $a_2=-0.257(1\pm5.49\delta-0.35\delta^2)/(1+\delta^2)$; $a_4=0.075\delta^2/(1+\delta^2)$. The measured anisotropy is also shown. The measured anisotropy limits the possible values of δ to $0\gtrsim\delta\geqslant-0.09$ and $4<\delta<5.6$.

[35] The angular distribution of the 5.83-Mev γ ray gave $W(\theta)=1+(0.7\pm0.3)\cos^2\theta+(1\pm0.5)\cos^4\theta$, with $A=1.75\pm0.4$. The positive value of A_4 rules out values of δ greater than -0.3 and, since δ is limited to $-0.7>\delta>-3$ for $A_4>0.5$, gives some indication that $-0.7\gtrsim\delta\gtrsim-3$. The anisotropy calculated for the $5.83\rightarrow0$ transition at the 2.11-Mev resonance assuming mixing of quadrupole and octupole radiation is quite similar to that for the 1.47-Mev resonance. The anisotropy measurement of the $5.83\rightarrow0$ transition at the 2.11-Mev resonance was quite uncertain (see Table VIII) but gives good agreement with the range of $|\delta|$ obtained from the 1.47-Mev resonance.

ing to $\delta<0$ is the proper choice is given by the limit on the $\cos^4\theta$ coefficient ($|A_4|<0.07$) obtained from the angular distribution measurement of the 5.10-Mev γ ray at the 2.11-Mev resonance (see Table V). For this distribution the coefficient of P_4 (see the caption of Fig. 14) is proportional to $5x-2$, where x is the fractional contribution of channel spin $S=0$ to the formation of the resonance. Using the algebraic relation between the two forms of the angular distribution function $W(\theta)=1+A_2\cos^2\theta+A_4\cos^4\theta\equiv 1+a_2P_2(\cos\theta)+a_4P_4(\cos\theta)$, it is found that the limit on A_4 corresponds to the limits $0.38<x<0.42$ for the positive range of δ allowed by the anisotropy measurement, while A_4 (and therefore a_4) is calculated to be negligible for all x for the negative range of δ allowed by the anisotropy measurement. Since x was determined to be (see Sec. IVB) 0.56 ± 0.12, the $5.10\rightarrow 0$ transition is most probably predominantly dipole.

C. Comparison with Previous Results

With the exception of the disagreement (see Sec. IIIC) with the anisotropy reported by Woodbury *et al.*[5] for the $8.90\rightarrow 5.83$ transition, the present work is in good agreement with previous investigations[1–5]

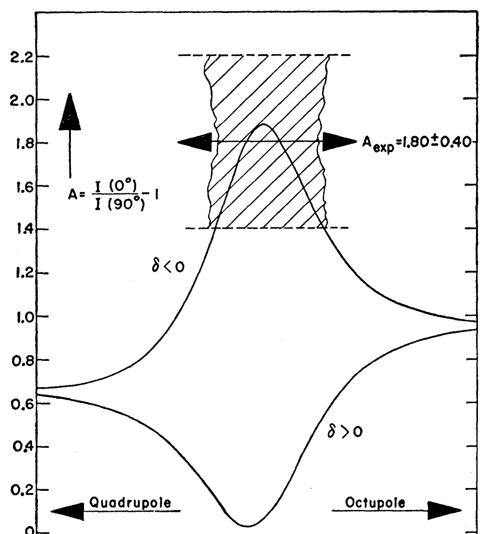

FIG. 13. The anisotropy of the 5.83 ($J=3$) $\rightarrow$ 0 ($J=1$) γ transition following the formation of the 3^-, N^{14} 8.90-Mev level by d-wave protons. The transition is assumed to be a mixture of quadrupole and octopole radiation with an intensity ratio $\delta^2=\Gamma_\gamma{}^f(3)/\Gamma_\gamma{}^f(2)$. This figure shows as a function of $|\delta|$ the anisotropy A of the angular distribution of the γ transition relative to the proton beam. Each one of the two curves corresponds to a definite sign of δ. The two curves were calculated from the theoretical angular distribution function: $W(\theta)=1+a_2P_2(\cos\theta)+a_4P_4(\cos\theta)$, where $a_2=0.367(1\pm0.87\delta+1.31\delta^2)/(1+\delta^2)$; $a_4=-0.050(1\pm4.67\delta-0.08\delta^2)/(1+\delta^2)$. The measured anisotropy is also shown. The measured anisotropy limits the possible values of δ to $-0.4>\delta>-4.0$.

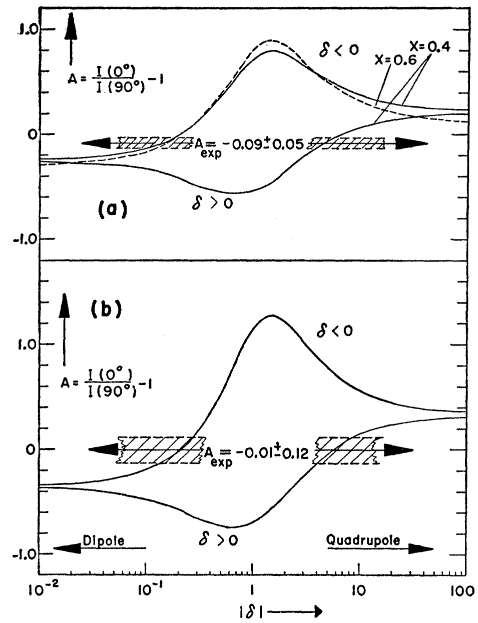

FIG. 14. The anisotropy of the 5.10 ($J=2$) $\rightarrow$ 0 ($J=1$) γ transition after formation, by d-wave protons, of (a) the 2^-, N^{14} 9.50-Mev level, and (b) the 3^-, N^{14} 8.90-Mev level. The transition is assumed to be a mixture of dipole and quadrupole radiation with an intensity ratio $\delta^2=\Gamma_\gamma{}^f(2)/\Gamma_\gamma{}^f(1)$. This figure shows as a function of $|\delta|$ the anisotropy A of the angular distribution of the γ transition relative to the proton beam. The measured anisotropy is shown for both (a) and (b). Each curve in (a) and (b) corresponds to a definite sign of δ. The curves were calculated from the theoretical angular distribution function: $W(\theta)=1+a_2P_2(\cos\theta)+a_4P_4(\cos\theta)$. For (a), $a_2=1.06(x+1)(-0.125\pm0.560\delta+0.089\delta^2)/(1+\delta^2)$, and $a_4=-0.81(5x-2)(0.254\delta^2)/(1+\delta^2)$. The anisotropy is shown for $x=0.4$ for $\delta>0$ and $x=0.6$ and 0.4 for $\delta<0$. The measured anisotropy limits the possible values of δ to $-0.1>\delta>-0.2$ and $3.6<\delta<6$ for $0.2<x<1.0$. For (b), $a_2=2.12(-0.125\pm0.560\delta+0.089\delta^2)/(1+\delta^2)$, and $a_4=0.197(0.254\delta^2)/(1+\delta^2)$, and the measured anisotropy limits the possible values of δ to $-0.14>\delta>-0.28$ and $4.0<\delta<8.6$.

of the 1.47- and 2.11-Mev resonances for the capture of protons by C^{13}. In particular, the spin assignments established in the present work (see Fig. 10) confirm the most probable spins assigned (see Sec. I) to the N^{14} 9.50-, 8.90-, 5.83-, and 5.10-Mev levels on the basis of these previous investigations. The only serious disagreement with the present work involves the spin assignment of $J=2$ given to the N^{14} 5.10-Mev level.

It has been suggested[6] that the intensity ratio of 1:2 for the $5.10\rightarrow 2.31$ transition to the $5.10\rightarrow 0$ transition (see Fig. 10) favors $J=1$ over $J=2$ for the N^{14} 5.10-Mev level because, for $J=2$, the quadrupole $5.10\rightarrow 2.31$ transition would be competing with a $5.10\rightarrow 0$ transition which could be dipole. However, a consideration of the inhibition[36,37] of $\Delta T=0$ magnetic transitions in self-conjugate nuclei, and the selection rule for $E1$ transitions in self-conjugate nuclei, leads to the conclusion that the observed branching ratio of

[36] G. Morpurgo, Phys. Rev. **110**, 721 (1958).
[37] E. K. Warburton, Phys. Rev. Letters **1**, 68 (1958).

the 5.10-Mev level is consistent with both $J=2$ and $J=1$.

Broude *et al.*[8] have investigated the $C^{13}(p,\gamma)N^{14}$ reaction at proton energies of 0.9 and 1.0 Mev, corresponding to N^{14} excitation energies of 8.46 and 8.37 Mev, respectively. They reported a transition to the N^{14} 5.10-Mev level and assigned this transition to the decay of the broad ($\Gamma=500$ kev)[4] N^{14} 8.70-Mev level which has $J^\pi=0^-$.[1,6] The partial width Γ_γ for the 8.70-Mev level was measured by Seagrave[4] to be $\Gamma_\gamma=51.2$ ev. Most of this width arises from the $8.70\rightarrow 0$ transition. If the transition to the 5.10-Mev level reported by Broude *et al.*[8] is assigned to the 8.70-Mev level, its intensity relative to the $8.70\rightarrow 0$ transition gives $\Gamma_\gamma{}^f=1.3$ ev. This width corresponds to Weisskopf matrix elements of 0.05, 1.6, 800, and 2.5×10^4 for $E1$, $M1$, $E2$, and $M2$ transitions, respectively, for a 3.32-Mev γ ray corresponding to a $8.42\rightarrow 5.10$ transition. Therefore, if in actual fact the 0^-, N^{14} 8.70-Mev level decays to the N^{14} 5.10-Mev level with the strength reported by Broude *et al.*,[8] the 5.10-Mev level must have $J=1$. Consequently, since the assignment of $J=2$ for the 5.10-Mev level seems to be conclusive, it is almost certain that the transition to the 5.10-Mev level reported by Broude *et al.* does not originate with the N^{14} 8.70-Mev level.

Some information as to the possible source of the transition to the 5.10-Mev level observed by Broude *et al.* was obtained from the present investigation of the $C^{13}(p,\gamma)N^{14}$ reaction at proton energies in the range $1.35<E_p<1.54$ Mev. The principal results obtained in this investigation consisted of the pair spectra taken with the thick C^{13} target at a proton energy of 1.40 Mev. The results obtained from these pair spectra were presented in Table III of Sec. IIIB. The decay scheme assignments of Table III are the same as given by Broude *et al.* except for the transitions involving the 5.10-Mev level, which were not observed in the present work (see Sec. IIIB) but were observed by Broude *et al.* The principal contribution to the γ-ray intensities of Table III should most certainly be due to the broad, N^{14} 8.70-Mev level which is centered at $E_p=1.25$ Mev.[4] Significant contributions to the decay modes listed in Table III from sharp resonances in the energy region investigated ($1.35<E_p<1.54$ Mev) in the present work are ruled out by the weak energy dependence of the γ-ray intensities and anisotropies. However, contributions from broad or relatively distant levels cannot be excluded. Therefore, the decay modes observed at $E_p=1.40$ Mev in the present work, and at $E_p=0.9$ and 1.0 Mev in the work of Broude *et al.*,[8] cannot be conclusively assigned to the N^{14} 8.70-Mev level.

A striking result of the pair spectra measurements (Table III) is the highly negative anisotropy of the 3.11-Mev γ ray corresponding to the $8.80\rightarrow 5.69$ transition. This anisotropy shows that the 3.11-Mev γ ray cannot arise from the 0^- 8.70-Mev level alone, and is somewhat suggestive of interference of the 8.70-Mev level with another level or with a nonresonant background. Since interference takes place, for overlapping resonances, through the same channel spin S, the 0^- 8.70-Mev level, which is formed by $S=0$ only, can interfere with resonances with $J^\pi=1^+$, 2^-, etc., and cannot, for example, interfere with the 3^- 8.90-Mev level. The 5.69-Mev level has $J=1$,[28] so that 1^+ and 2^- are the only alternatives for the level interfering with the 0^- 8.70-Mev level if the 3.11-Mev γ ray is dipole. An attempt was made to ascertain the parity of the interfering level (if any) by measuring the angular distribution of the 3.11-Mev γ ray at $E_p=1.40$ Mev from single-crystal spectra. The interference term in the angular distribution would be proportional to $\cos\theta$ if the interfering level were of even parity.[24] Angular distribution data were obtained at angles to the beam from 0° to 150°, and it was found that any terms in odd powers of $\cos\theta$—if actually present—were small compared to terms in even powers of $\cos\theta$. Thus the anisotropy of the 3.11-Mev γ ray cannot be caused by interference of the 8.70-Mev level with an even parity level. The anisotropy of the 3.11-Mev γ ray obtained from the single-crystal spectra was in good agreement with the pair spectra measurement (Table III).

The N^{14} 4.91-Mev level has been given a most probable assignment of $J^\pi=0^-$.[6] The parity assignment is based on analysis of the $C^{13}(d,n)N^{14}$ reaction[26] which gives a strong indication that the 4.91-Mev level is $J^\pi=0^-$ or 1^-. The 4.91-Mev level has been observed to decay by γ emission to the $T=0$, N^{14} ground state but not to the $T=1$, 0^+, N^{14} 2.31-Mev level.[6] If the 4.91-Mev level (which is assumed to be $T=0$) where $J^\pi=1^-$, it would be expected to decay preferentially by $E1$ radiation to the 2.31-Mev level since $E1$ radiation to the ground state is an isotopic-spin forbidden transition. Therefore, the evidence for $J^\pi=0^-$ is rather strong. If the 4.91-Mev level were $J^\pi=0^-$, a γ transition to it from the 0^-, N^{14} 8.70-Mev level would, of course, be forbidden.

The highly negative anisotropy of the $8.80\rightarrow 5.69$ transition, the observation of a cascade to the 4.91-Mev level at $E_p=0.9$ and 1.0 Mev in the work of Broude *et al.*[8] and in the present work, and the observation of a cascade to the 5.10-Mev level by Broude *et al.*,[8] but not in the present work, cannot be fully explained at the present time. A possible explanation of the appearance of the cascades to the 5.10- and 4.91-Mev levels at $E_p=0.9$ and 1.0 Mev as reported by Broude *et al.*[8] is that these cascades are due to a resonance approximately midway between these two energies (i.e., between 8.37 and 8.46 Mev in N^{14}). A level (or levels) in this energy range (at 8.45 ± 0.07 Mev in N^{14}) has been observed[38] by means of the $N^{14}(\alpha,\alpha')N^{14}$ reaction. However, it seems most probable that the same broad level or nonresonant background that gives rise to the highly

[38] Miller, Carmichael, Gupta, Rasmussen, and Sampson, Phys. Rev. **101**, 740 (1956).

negative anisotropy of the $8.80 \rightarrow 5.69$ transition is responsible for the cascades to the 4.91- and 5.10-Mev levels. The anisotropy measurement of the 3.89-Mev γ ray (see Table III) gives some indication that the cascade to the 4.91-Mev level does not arise from a spin-zero level.

It would seem that a careful investigation of the $C^{13}(p,\gamma)N^{14}$ reaction in the energy region $0.8 \lesssim E_p \lesssim 1.6$ Mev will have to be made before these anamolies are understood and the decay scheme of the N^{14} 8.70-Mev level is established.||

V. COMPARISON WITH SHELL-MODEL SYSTEMATICS

A. Introduction

A shell-model calculation of the non-normal energy level spectrum of mass 14, such as the recent calculations on mass[39] 15 and mass[40] 16, would be a formidable task. In lieu of such a calculation, and in order to provide an orientation in the event that such a calculation were to be undertaken, it is desirable to have a qualitative description of the odd-parity spectrum of mass 14. Towards this end, then, this section is devoted to a comparison of the odd-parity states of mass 14 with expectations based on the work on neighboring nuclei and to a discussion of these levels from the viewpoint of simplifying assumptions. It is recognized that much of this section is speculative in nature; but it is hoped that, at the least, this discussion will serve as a stimulus to further work

The energy level diagrams of N^{14} and C^{14} are displayed in Fig. 15. The diagram for C^{14} is taken from Warburton and Rose.[17] The diagram for N^{14} is taken from Ajzenberg and Lauritsen[6] apart from later additions and corrections—which include the results of the present paper. A few remarks concerning some of these changes are necessary. The spin-parity assignments given to the N^{14} 5.69- and 6.23-Mev levels are from the work of Wilkinson and Bloom.[28] The spin-parity assignments for all the other N^{14} levels below 7.1 Mev have been reviewed in the present paper or are the same as given by Ajzenberg and Lauritsen.[6] The 9.16- and 10.43-Mev levels were both previously given $J^\pi = 2^-$ as the most probable assignment[5,6,41]; the reason why a preference for odd-parity is not indicated for these levels in Fig. 15 has been discussed in a recent paper.[42]

In the N^{14} energy level diagram of Fig. 15 known $T=1$ states are indicated, known $T=0$ states are not. The $T=1$ assignments for the N^{14} levels above 8 Mev

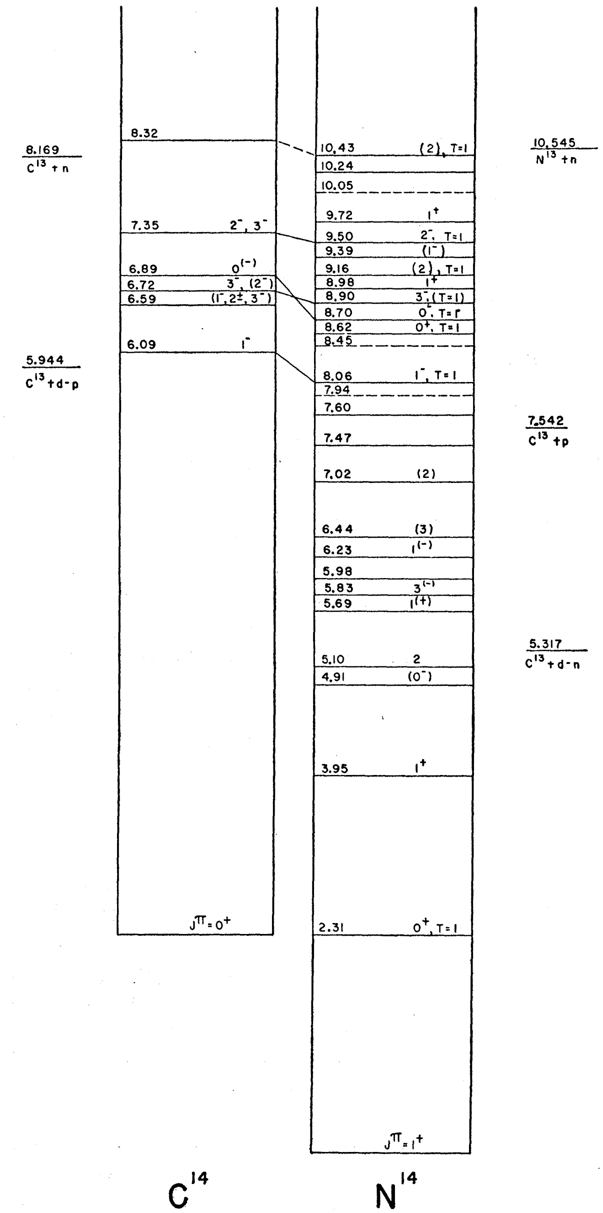

FIG. 15. Energy levels of C^{14} and N^{14}. The references for the information given in the C^{14} energy level diagram are given in reference 17. The information for the N^{14} energy level diagram was obtained from the compilation of Ajzenberg and Lauritsen (reference 6) except for later additions and corrections (see text). Uncertain or less likely assignments are enclosed in parentheses. Uncertain levels are denoted by dashed lines. The $T=1$ assignments are indicated, $T=0$ assignments are not. The C^{14} ground state is matched in energy with its isotopic-spin analog in N^{14} at 2.31 Mev in order to exhibit the correspondence of levels belonging to isotopic-spin triads. Levels for which the correspondence seems well-established are connected by solid lines, while levels for which the correspondence is less certain are connected by dashed lines.

are based on the observation of dipole transitions—from these levels to known $T=0$ levels—with strengths greater than allowed for $\Delta T=0$ transitions by the selection rules for $M1$[36,42] and $E1$ transitions in self-

|| *Note added in proof*.—The most likely explanation of the decays to the 4.91-, 5.10-, and 5.69-Mev levels is direct radiative capture of p-wave protons as proposed by Warburton *et al.* [Warburton, Pinkston, Rose, and Hatch, Bull. Am. Phys. Soc. Ser. II, **4**, 219 (1959)].

[39] E. C. Halbert and J. B. French, Phys. Rev. **105**, 1563 (1957).

[40] J. P. Elliott and B. H. Flowers, Proc. Roy. Soc. (London) **A242**, 57 (1957).

[41] Willard, Bair, Cohn, and Kington, Phys. Rev. **105**, 202 (1957).

[42] E. K. Warburton, Phys. Rev. **113**, 595 (1959).

conjugate nuclei. The $T=1$ assignments for the 8.62-, 8.90-, 9.16-, 9.50-, and 10.43-Mev levels have been discussed in a recent paper.[42] The uncertain levels at 7.94, 8.45, and 10.05 Mev have been observed by the $N^{14}(\alpha,\alpha')N^{14}$ reaction[38] only, and thus are assigned $T=0$. There is no conclusive evidence concerning the isotopic spin of the other levels above 7.4 Mev in N^{14} for which a preference for $T=1$ has not been indicated. Except for the 2.31-Mev level, there is good evidence for an assignment of $T=0$ to all of the N^{14} states below 7.4 Mev.[6,28,38,42]

B. $T=1$, Odd-Parity States of Mass 14

The large proton reduced widths[2,6] of the N^{14} 1^- 8.06-, 0^- 8.70-, 3^- 8.90-, and 2^- 9.50-Mev levels indicate that these levels belong predominantly to the s^4p^92s and s^4p^91d configurations with the ground state of C^{13} as their main parent. The description of the 8.06- and 8.70-Mev levels as s^4p^92s has been suggested previously.[28,43] The strong $E1$ transitions[6] of these two levels to the s^4p^{10} states of N^{14} is in accord with this description. Because of the large (≈ 5 Mev) splitting of the $1d_{\frac{5}{2}}$ and $1d_{\frac{3}{2}}$ orbitals, it would be expected that the $T=1$ levels at 8.90 and 9.50 Mev in N^{14}, which are formed by capture of d-wave protons, are largely $d_{\frac{5}{2}}$ levels. For a $J^\pi=2^-$, $d_{\frac{5}{2}}$ level the fractional contribution of channel spin $S=0$ in the formation of the level by capture of d-wave protons is calculated to be $x=0.6$. For a $J^\pi=2^-$, $d_{\frac{3}{2}}$ level, x is calculated to be 0.4. Therefore, the value of $x(=0.56\pm0.14)$ determined for the 2^-, N^{14} 9.50-Mev level in the present work is consistent with the N^{14} 9.50-Mev level belonging to the $s^4p^9d_{\frac{5}{2}}$ configuration, but does not rule out large admixtures of $s^4p^9d_{\frac{3}{2}}$. Zipoy *et al.*,[2,3] using the value $x=0.6$, obtained a good fit to the angular distributions of the protons elastically scattered from the N^{14} 9.50-Mev level.

We consider next the reduced widths of the N^{14} 8.06-, 8.70-, 8.90-, and 9.50-Mev levels and the known odd-parity levels of C^{14}. These reduced widths give valuable information relating to the configurational mixing of the states involved and to the correspondence of levels belonging to isotopic-spin triads. The neutron reduced widths of C^{14} were obtained by analysis of the $C^{13}(d,p)C^{14}$ reaction, while the proton reduced widths of N^{14} were obtained from the resonant capture of protons by C^{13}. Since the relation between stripping and resonant reduced widths is rather obscure, the widths of the C^{14} and N^{14} levels are compared to the respective stripping and resonant single-particle reduced widths.

Reduced Widths

In general the reduced width for a single-nucleon emission can be written in the form[44]

$$\theta^2=\mathcal{S}\theta_0^2, \tag{2}$$

where θ_0^2 is the single-particle reduced width and $\mathcal{S}$ (hereafter called the relative reduced width) is the probability that the heavier nucleus will arrange itself in a configuration corresponding to the lighter nucleus plus a nucleon. For the case considered here—that of the transfer of a nonequivalent nucleon—$\mathcal{S}$ is limited by $\mathcal{S}\leqslant 1$, where $\mathcal{S}=1$ corresponds to a state completely described as a nonequivalent nucleon bound to the ground state of the lighter nucleus. The most reliable procedure for obtaining a value for $\theta_0^2(s)$ or $\theta_0^2(d)$ for both resonant and stripping reactions is to measure the reduced width of a "single-particle" reaction [such as $O^{16}+n$ or $O^{16}(d,p)O^{17}$] leading to s or d states of a "closed-shell-plus-one" nucleus. Alternatively, a lower limit for $\theta_0^2(s)$ or $\theta_0^2(d)$ can be obtained from the observed width for a process which adds a $2s$ or $1d$ nucleon to an unfilled s^4p^n core. An example of the latter is the resonant capture of protons by C^{12} into the N^{13}, $s_{\frac{1}{2}}$, 2.37-Mev and $d_{\frac{5}{2}}$, 3.56-Mev levels or the "mirror" reaction, $C^{13}(d,p)C^{13}$, leading to the $2s_{\frac{1}{2}}$ and $d_{\frac{5}{2}}$ states at 3.09 and 3.86 Mev in C^{13}. There is theoretical and experimental evidence[39,45] that for these mass-13 levels $\mathcal{S}\sim 1$, and in the discussion of the resonant reduced widths of N^{14} it will be assumed that the reduced widths for the capture of protons by the N^{13} 2.37- and 3.56-Mev levels have the single-particle value.

Both the resonant and stripping reduced widths are given here in units of $3(T_i\tfrac{1}{2}T_{zi}t_z;\, T_fT_{zf})^2\hbar^2/2\mu a$, where $(T_i\tfrac{1}{2}T_{zi}t_z;\, T_fT_{zf})$ is the isotopic-spin vector addition coefficient for a neutron ($t_z=\frac{1}{2}$) or proton ($t_z=-\frac{1}{2}$) reduced width, μ is the reduced mass of the system, and a is the interaction radius.

The C^{14} Reduced Widths.—From the various experiments on the $O^{16}(d,p)O^{17}$ reaction,[6] Halbert and French[39] estimate that the best values for $\theta^2(s)$ and $\theta_0^2(d)$, extracted from the stripping cross sections to the $s_{\frac{1}{2}}$ and $d_{\frac{5}{2}}$ levels of O^{17}, are $\theta_0^2(s)\simeq 0.3$ and $\theta_0^2(d)\simeq 0.1$. These values are in good agreement with the stripping reduced widths of $\theta^2(s)=0.28$ and $\theta^2(d)=0.12$ obtained for the $C^{12}(d,p)C^{13}$ reaction[46] (with $E_d=14.8$ Mev) leading to the 3.09- and 3.86-Mev levels of C^{13}.[47]

In Table IX are listed the stripping reduced widths calculated[47] from the expermental $C^{13}(d,p)C^{14}$ angular distributions[46] for the six known bound states of C^{14}. These results have not been previously published and so are given here in some detail. The first four columns of Table IX give the experimental results, column 5 gives the spin-parity assignments corresponding to the pairing (discussed below) of C^{14} and N^{14} levels shown in Fig. 15, and column 6 gives the reduced widths corresponding to the spin-parity assignments of column 5.[48]

[43] A. M. Lane, Massachusetts Institute of Technology, 1955 (unpublished).

[44] J. B. French, Phys. Rev. **103**, 1391 (1956).

[45] A. M. Lane, Proc. Phys. Soc. (London) **A68**, 197 (1955).

[46] McGruer, Warburton, and Bender, Phys. Rev. **100**, 235 (1955).

[47] These widths were calculated from the stripping results (reference 46) by E. U. Baranger (unpublished). We are grateful to Dr. Baranger for permission to publish her data.

[48] In some cases the values of $(2J+1)\theta^2$ given in Table IX corroborate the spin assignments of column 4. For the $C^{13}(d,p)C^{14}$

TABLE IX. Stripping reduced widths from the $C^{13}(d,p)C^{14}$ reaction

C^{14} level (Mev)	l_n [a]	$(2J+1)\theta^2$ [b]	J^π [c]	J^π [d]	θ^2 [e]
Ground state	1	0.10	0^+	0^+	0.10
6.09	0[f]	1.20	1^-	1^-	0.40
6.59	2	0.014	$1^-, 2^-, 3^-$	···	<0.01
	1+3	0.007 ($l_n=1$), 0.014 ($l_n=3$)	2^+		
6.72	2	0.78	$3^-, (2^-)$	3^-	0.11
6.89	0	0.39	$0^{(-)}$	0^-	0.39
7.35	2	0.53	$2^-, 3^-$	2^-	0.11

[a] The values for l_n (orbital angular momentum transferred in the stripping process) are those given in reference 46 except for the 6.59- and 6.89-Mev levels which are discussed in reference 17 and for which the l_n values are not definitely established.
[b] Calculated by Baranger (reference 47) from the results of McGruer *et al.* (reference 46). An uncertainty of 50% was originally assigned to the absolute cross sections from which these reduced widths are calculated (see reference 46); however, later work [E. K. Warburton and J. N. McGruer (unpublished)] has reduced this uncertainty to 25%. The relative cross sections are accurate to ±10%. The reduced width for the 6.89-Mev level is extremely dependent on the assumed value of the interaction radius. This dependence introduces an additional uncertainty of ±25% in the reduced width for this level.
[c] Possible assignments (see Fig. 15).
[d] These assignments are those of the assumed analog states in N^{14} (see Fig. 15).
[e] These values of θ^2 were obtained from column 3 using the spin values of column 5.
[f] No detectable reduced width for $l_n=2$ ($\theta_d^2 \leqslant 0.015$).

A comparison of the reduced widths of the C^{14} 6.09^-, 6.72-, 6.89-, and 7.35-Mev levels given in the last column of Table IX with the single-particle stripping reduced widths shows that, within the experimental uncertainty, all four levels have $\mathcal{S}=1$ for the spin-parity assignments indicated by the pairing of C^{14} and N^{14} levels shown in Fig. 15.

The N^{14} *Reduced Widths.*—The proton reduced width of the $\frac{1}{2}^+$, N^{13} 2.37-Mev level constitutes the most reliable estimate of the resonant single-particle reduced width $\theta_0^2(s)$, while the proton reduced width of the $\frac{5}{2}^+$, N^{13} 3.56-Mev level and the reduced width for the resonant capture of neutrons by O^{16} into the $d_{\frac{5}{2}}$ O^{17} 5.08-Mev level give the most reliable estimates of the resonant single-particle reduced width $\theta_0^2(d)$.[39] Therefore, it is convenient to compare the resonant reduced widths of the N^{14} 2s- and d-states to those of N^{13}—and thus to the single-particle values—as a function of the interaction radius. By this means the usual uncertainties in resonant reduced widths due to the correction for the Thomas shift[49] and the extraction of the barrier penetrability are minimized.

The resonant reduced widths of the two N^{13} levels and the two s-wave resonances of N^{14} were calculated using the values of the level widths Γ given by Ajzenberg and Lauritsen,[6] while the experimental values of Γ given in the present paper were used to obtain the reduced widths of the two N^{14} d-wave resonances. For

reaction, $l_n=0$ and $l_n=2$ correspond to possible C^{14} spin-parity assignments of 0^-, 1^-, and 1^-, 2^-, 3^-, respectively. The stripping reduced widths, $\theta^2(s)$ and $\theta^2(d)$, for C^{14} must be less than or equal to the corresponding values: $\theta_0^2(s)\simeq 0.3$ and $\theta_0^2(d)\simeq 0.1$. Therefore, the values of $(2J+1)\theta^2$ given in Table IX are inconsistent with spin assignments of $J=0$ to the C^{14} 6.09-Mev level and of $J=1$ to the C^{14} 6.72-Mev level. Furthermore, the values of $(2J+1)\theta^2$ give a preference for the assignment $J=3$ for the 6.72-Mev level and for one of the assignments $J=2$ or 3 for the C^{14} 7.35-Mev level.

[49] R. G. Thomas, Phys. Rev. **88**, 1109 (1952).

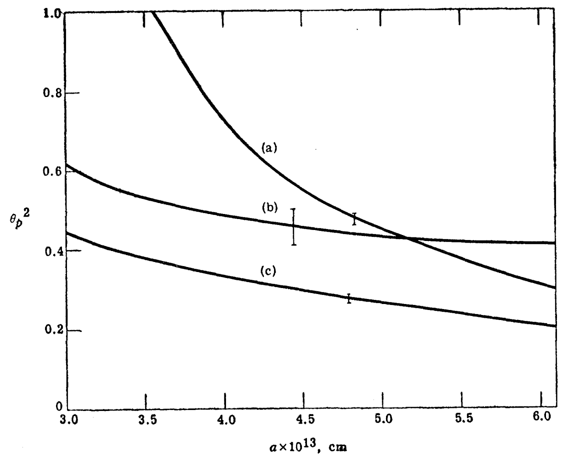

FIG. 16. Proton reduced widths for the capture of s-wave protons by carbon as a function of the interaction radius a. The dimensionless reduced width θ_p^2 is defined as $2\mu a\gamma^2/3\hbar^2(T_i\tfrac{1}{2}T_{zi}t_z;\,T_fT_{zf})^2$, where μ is the reduced mass of the system, γ^2 is the usual reduced width, and $(T_i\tfrac{1}{2}T_{zi}t_z;\,T_fT_{zf})$ is the isotopic-spin coupling factor. (a) the $\frac{1}{2}^+$, N^{13} 2.37-Mev level, (b) the 0^-, N^{14} 8.70-Mev level, and (c) the 1^-, N^{14} 8.06-Mev level. The error flags represent the experimental uncertainties in Γ.

the s-wave resonances of both nuclei a correction was made for the Thomas shift.[49] For the d-wave resonances the Thomas shift was found to be negligible compared to the experimental uncertainty in Γ, so that the d-wave proton reduced widths are given by

$$\theta_p^2(d)=\frac{\mu a}{3\hbar^2k}\frac{(F^2+G^2)}{(T_i\tfrac{1}{2}T_{zi}t_z;\,T_fT_{zf})^2}\Gamma, \qquad (3)$$

where F and G are the regular and irregular solutions, respectively, of the Coulomb field evaluated at the interaction radius a, and $k=2\pi$ divided by the de Broglie wavelength of the proton in the c.m. system. The s-wave reduced widths are shown in Fig. 16, while the d-wave reduced widths are shown in Fig. 17. The two N^{13} reduced widths and the s-wave widths of N^{14} are in agreement with the reduced widths previously given[6] for specific values of the interaction radius a.

The theoretical work of Thomas[49] on the N^{13} levels indicates a preference for a value of the interaction radius in the range $(4.4-4.9)\times10^{-13}$ cm. For $a=4.7\times10^{-13}$ cm, the reduced widths from Fig. 16 are $\theta^2(s)=0.50$, 0.29, and 0.44 for the N^{13} 2.37-Mev level and the N^{14} 8.06- and 8.70-Mev levels, respectively, and the reduced widths from Fig. 17 are $\theta^2(d)=0.23$, 0.21, and 0.17 for the N^{13} 3.56-Mev level and the N^{14} 8.90- and 9.50-Mev levels, respectively. Assuming that $\mathcal{S}=1$ for the N^{13} levels, the corresponding relative reduced widths are $\mathcal{S}\simeq 0.6$, 0.9, 0.9, and 0.7 for the N^{14} 8.06-, 8.70-, 8.90-, and 9.50-Mev levels, respectively. The relative reduced widths of the s states have an estimated uncertainty of 30%, mainly due to the ambiguity in the interaction radius; while those of the d states have an estimated uncertainty of 20%, mainly due to the experimental uncertainty in Γ.

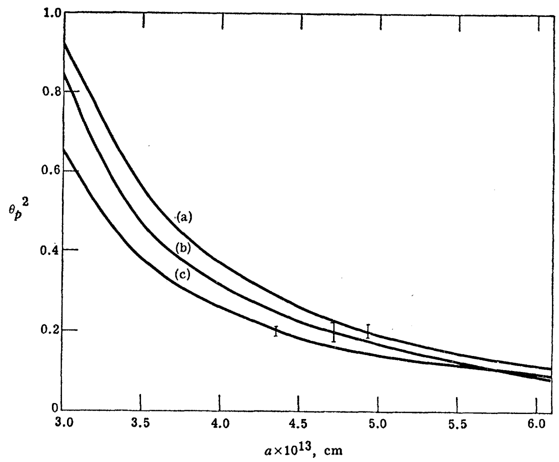

FIG. 17. Proton reduced widths for the capture of d-wave protons by carbon as a function of the interaction radius a. The dimensionless reduced θ_p^2 is defined as $2\mu a\gamma^2/3\hbar^2(T_i\frac{1}{2}T_{zi}t_z;\, T_fT_{zf})^2$, where μ is the reduced mass of the system, γ^2 is the usual reduced width, and $(T_i\frac{1}{2}T_{zi}t_z;\, T_fT_{zf})$ is the isotopic-spin coupling factor. (a) the $\frac{5}{2}^+$, N^{13} 3.56-Mev level, (b) the 3^-, N^{14} 8.90-Mev level, and (c) the 2^-, N^{14} 9.50-Mev level. The error flags represent the experimental uncertainties in Γ.

Comparison of the C^{14} *and* N^{14} *Levels*

Assuming charge independence, the relative reduced widths of analog states in C^{14} and N^{14} are expected to be the same. While the large proton reduced widths of the N^{14} 8.06-, 8.70-, 8.90-, and 9.50-Mev levels and the large neutron reduced widths of the C^{14} 6.09-, 6.72-, 6.89-, and 7.35-Mev levels practically guarantee that the C^{14} analogs of these N^{14} states have been observed and *vice versa*. The C^{14} 6.59-Mev level is ruled out as a possible analog of the four N^{14} levels in question, since the relative reduced width of this level is an order of magnitude smaller than for these N^{14} levels. Likewise, the N^{14} 9.16-Mev level, which would have[10,50] $\theta^2(d)\simeq1.3\times10^{-3}$ if it were formed by d-wave protons, is eliminated as a possible analog of the C^{14} 6.09-, 6.72-, 6.89-, and 7.35-Mev levels. Therefore, for reasonable values of the energy displacement of $C^{14}-N^{14}$ analog states, the correspondence of isotopic-spin triads shown in Fig. 15 is the only one consistent with the spin-parity and isotopic-spin assignments and the reduced widths of the levels involved. The correspondence of the $s_{\frac{1}{2}}$ states at 6.09 and 6.89 Mev in C^{14} with the $s_{\frac{1}{2}}$ states at 8.06 and 8.70 Mev in N^{14} has been suggested previously.[6]

The relative energy positions of the odd-parity analog states can be shown to be reasonable using the procedure of Elliott and Flowers,[40] which lumps together the Coulomb correction and the Thomas[49] shift,

$$\Delta E_J=\tfrac{1}{2}\Delta p+\tfrac{1}{2}(C_J{}^d\Delta d+C_J{}^s\Delta s)+0.155, \qquad (4)$$

where ΔE_J is the energy difference in Mev between the excitation in C^{14} and the excitation in N^{14} of a state with spin J, Δp is the observed energy difference between C^{13} and N^{13}, Δd and Δs are the energy differences between the $d_{\frac{5}{2}}$ and $2s_{\frac{1}{2}}$ states of C^{13} and N^{13}, and the constants $C_J{}^s$ and $C_J{}^d$ give the configurational mixture of the state $J(C_J{}^s+C_J{}^d=1)$. The constant 0.155 Mev is the difference in the ground-state energies of N^{14} and C^{14}.[6] From Eq. (4), assuming that the C^{14} 6.09- and 6.89-Mev levels are pure $2s$ states and the C^{14} 6.72- and 7.35-Mev levels are pure d states, the analogs of these four states are calculated to have excitation energies in N^{14} of 8.10, 8.91, 8.95, and 9.57 Mev, respectively. These energies are to be compared to 8.06, 8.70, 8.90, and 9.50 Mev, respectively, these being the energies of the observed N^{14} states assigned as analogs of the C^{14} 6.09-, 6.89-, 6.72-, and 7.35-Mev levels. An admixture of the $s^4p^92s_{\frac{1}{2}}$ configuration of $\sim$30% in intensity (i.e., $C_J{}^s\sim0.3$) to the predominantly $s^4p^9d_{\frac{5}{2}}$ states would bring the calculated and observed energy displacements of the $J^\pi=2^-$, and 3^- analogs in exact agreement, while an admixture of s^4p^9d to the predominantly $s^4p^22s_{\frac{1}{2}}$ states would increase the disagreement of the calculated and observed energy displacements of the $J^\pi=0^-$ and 1^- analogs. However, because of the questionable approximations made in obtaining Eq. (4) it is not justifiable to draw any conclusions as to the configurational mixture of the s- and d-states from a comparison of these calculated and observed energy displacements.

The poor agreement of the observed and calculated energy displacement for the 0^- levels reflects the difference of 160 kev in the splitting of the 0^- and 1^- levels in C^{14} and N^{14}. A possible explanation of this difference depends on the proposal of Wilkinson and Bloom[28] that the $T=1$, 1^-, N^{14} 8.06-Mev level and its $T=0$ counterpart (assumed to be the N^{14} 6.23-Mev level[28]) interact with one another with the result that each of these levels has an isotopic-spin impurity of $\sim$7% in intensity. The repulsion of these levels might be a possible explanation for the smaller separation of the 0^- and 1^-, $T=1$ levels in N^{14} compared to the separation of the analog states in C^{14}.

Except for the 1^- levels, the relative reduced widths obtained for the C^{14} levels agree within the rather large uncertainties with those obtained for their N^{14} analogs. However, the relative reduced widths obtained from the proton widths of the N^{14} levels give some indication that the odd-parity $T=1$ states under consideration are not completely describable as pure $2s_{\frac{1}{2}}$ or $d_{\frac{5}{2}}$ states with the ground state of C^{13} as their only parent. Assuming that these odd-parity states contain contributions from s^4p^92s and s^4p^9d only, it seems reasonable that admixtures of $d_{\frac{3}{2}}$ coupled to the C^{13} ground state and $2s_{\frac{1}{2}}$ and $d_{\frac{5}{2}}$ coupled to the $J^\pi=\frac{3}{2}^-$ first excited state of s^4p^9 are more likely than admixtures of $d_{\frac{3}{2}}$ coupled to the $J^\pi=\frac{3}{2}^-$ first excited state of s^4p^9. The fact that the $J^\pi=0^-$ and 3^- N^{14} states have larger relative reduced widths than the $J^\pi=1^-$ and 2^- N^{14} states, respectively, is consistent with this argument.

Formation of the $J^\pi=1^-$ level in C^{14} or N^{14} by the

[50] J. B. Marion and F. B. Hagedorn, Phys. Rev. 104, 1028 (1956).

capture of either a $2s_{\frac{1}{2}}$ or a $d_{\frac{3}{2}}$ nucleon by the C^{13} ground state is consistent with the conservation of angular momentum. Therefore, the limit on $\theta^2(d)$ for the 1^-, C^{14} 6.09-Mev level (see Table IX) gives a limit of $\mathcal{S}\leqslant 0.15$ for the admixture of the configuration describable as a $d_{\frac{3}{2}}$ nucleon coupled to the C^{13} ground state in the predominantly $s^4p^92s_{\frac{1}{2}}$, $J^\pi=1^-$, C^{14} 6.09-Mev or N^{14} 8.06-Mev level.[51]

C. $T=0$, Odd-Parity Levels of N^{14}

At various times the N^{14} 4.91-Mev[52,53] level has been proposed as the $T=0$, 0^-, $s^4p^92s_{\frac{1}{2}}$ counterpart of the $T=1$, 0^-, $s^4p^92s_{\frac{1}{2}}$ state at 8.70 Mev in N^{14}; while both the 5.69-Mev[53] and 6.23-Mev[28] levels have been proposed as the $T=0$, 1^-, $s^4p^92s_{\frac{1}{2}}$ counterpart of the $T=1$, 1^-, $s^4p^92s_{\frac{1}{2}}$ state at 8.06 Mev in N^{14}. If the 4.91-Mev level and either the 5.69-Mev level or the 6.23-Mev level are the 0^- and 1^- states in question, the energy positions of the N^{14} 5.10- and 5.83-Mev levels are consistent with their being the $T=0$ counterparts of the $T=1$, $s^4p^9d_{\frac{5}{2}}$ states at 9.50 and 8.90 Mev in N^{14}. Some information on the reduced widths of these five $T=0$ levels is provided by the observation of the γ rays following the bombardment of C^{13} by deuterons by Ranken *et al.*[54] and the $C^{13}(d,n)N^{14}$ stripping results of Benenson.[26]

Ranken *et al.*[54] have measured the differential cross section for the γ rays emitted at 0° to the beam following bombardment of C^{13} by 4.5-Mev deuterons. Assuming isotropic distributions of the γ rays, they obtained cross sections of 131, 19, and 27 mb for the C^{14} 6.09-Mev γ ray and the N^{14} 5.69- and 4.91-Mev γ rays, respectively. Since the C^{14} 6.89-Mev level decays 100% to the C^{14} 6.09-Mev level,[17] the cross section of the 6.09-Mev γ ray represents the sum of the cross sections for the formation of the C^{14} 6.89- and 6.09-Mev levels by the capture of s-wave neutrons by C^{13}. If it is assumed that feeding of the 5.69-Mev and 4.91-Mev levels by higher-lying N^{14} states is negligible, and account is taken of the known branching ratio of the 5.69-Mev level, the cross sections of the 4.91-Mev and 5.69-Mev γ rays lead to cross sections of 27 and 50 mb, respectively, for the formation of these levels by $C^{13}(d,n)N^{14}$—again assuming s-wave nucleon capture (and thus isotropic distribution of the γ rays). The ratio of cross sections of 131:50:27 discussed above is to be compared to the ratio $\sim$8:3:1 predicted by simple stripping theory for $\sigma(C^{14}\ 6.89+6.09):\sigma(N^{14}\ 5.69):\sigma(N^{14}\ 4.91)$ assuming $\mathcal{S}\approx 1$ for all four states and 0^- and 1^- for the N^{14} 4.91- and 5.69-Mev levels, respectively. Considering the nature of the approximations made, it can be said that the results of Ranken *et al.* are quite consistent with $\mathcal{S}\approx 1$ and 0^- and 1^- for the N^{14} 4.91- and 5.69-Mev levels, respectively. Ranken *et al.*[54] did not observe any γ rays corresponding to the decay of the N^{14} 6.23-Mev level; however, a weak 3.9-Mev γ ray corresponding to the $6.23\rightarrow 2.31$ transition has been observed at $E_d=2.0$ Mev.[6]

It is difficult to obtain the relative reduced widths of the C^{14} 6.72- and 7.35-Mev levels and the N^{14} 5.10- and 5.83-Mev levels from the measurements of Ranken *et al.*, since the γ rays corresponding to the decay of these levels are not necessarily isotropic and, in addition, the uncertainties in the γ ray intensity measurements and the uncertainties in the branching ratios of the C^{14} 7.35-Mev level and the N^{14} 5.83- and 5.10-Mev levels are accumulative. However, assuming the C^{14} 6.72-Mev level has $J^\pi=3^-$, the N^{14} 5.10- and 5.83-Mev levels have $J^\pi=2^-$ and 3^-, respectively, and all three levels are formed by capture of d-wave nucleons, the results of Ranken *et al.* are consistent with $\mathcal{S}\approx 1$ for the N^{14} 5.83-Mev level and give some indication that the N^{14} 5.10-Mev level has $\mathcal{S}<1$.

From observations of the relative intensities of the neutron groups in the $C^{13}(d,n)N^{14}$ stripping results of Benenson,[26] it would appear that the N^{14} 4.91-Mev level has a proton reduced width at least a factor of five larger than that of the N^{14} 6.23-Mev level if both levels are formed by capture of s-wave protons and have $J^\pi=0^-$ and 1^-, respectively. Furthermore, the angular distribution of the neutron group corresponding to the N^{14} 6.23-Mev level is not in good agreement with that expected for capture of s-wave protons. In the results of Benenson the neutron groups corresponding to the N^{14} 5.69- and 5.83-Mev levels are obscured by the neutron group corresponding to the $C^{12}(d,n)N^{13}$ ground state reaction, while the neutron group corresponding to the N^{14} 5.10-Mev level is obscured by the more intense neutron group corresponding to the N^{14} 4.91-Mev level. Therefore, his results give very little information on the 5.10-, 5.69-, and 5.83-Mev levels. Benenson suggested a slight preference for p-wave proton capture by the 5.10-Mev level, but formation by d-wave protons also seems consistent with his results.

In summary, the rather meager experimental information on the nucleon reduced widths of the N^{14} 4.91-, 5.10-, 5.69-, 5.83-, and 6.23-Mev levels is consistent with the 4.91- and 5.83-Mev levels being the $T=0$ counterparts of the $T=1$, N^{14} 8.70- and 8.90-Mev levels, respectively; gives some indication that the N^{14} 5.10-Mev level contains considerable configura-

[51] This result is in contradiction to the conclusion of Broude *et al.* (reference 8). In an investigation of the $C^{13}(p,\gamma)N^{14}$ reaction at the $E_p=0.55$-Mev resonance (corresponding to the N^{14} 8.06-Mev level), they observed a small anisotropy in the ground-state transition which increased with increasing proton energy. From an analysis of this anisotropy they concluded that the d-wave contribution to the formation of this resonance corresponds to $\theta^2(d)\approx 0.9$. Since $\theta_0{}^2(d)\approx 0.23$, this value of $\theta^2(d)$ would correspond to $\mathcal{S}\approx 4$ which is impossible. We believe that the anisotropy observed by Broude *et al.* is further evidence of a nonresonant background in the $C^{13}(p,\gamma)N^{14}$ reaction (see Sec. IVC) rather than an indication of a d-wave contribution to the formation of the 1^-, N^{14} 8.06-Mev level.

[52] D. R. Inglis, Revs. Modern Phys. **25**, 390 (1953).

[53] Broude, Green, Singh, and Willmott, Phil. Mag. **2**, 499 (1957).

[54] Ranken, Bonner, McCrary, and Rabson, Phys. Rev. **109**, 917 (1958).

tional admixtures if, in actual fact, it is the $J^\pi=2^-$ state in question; and strongly favors the 5.69-Mev level, rather than the 6.23-Mev level, as the $T=0$ counterpart of the $T=1$, 1^-, N^{14} 8.06-Mev level. The 5.69-Mev level was assigned $J^\pi=1^{(+)}$ in Fig. 15. This assignment is in contradiction with an identification of it as a 1^-, $s^4p^92s_{\frac{1}{2}}$ state; however, consideration of the experimental evidence leading to the assignment of even-parity shows that it is not at all conclusive.

Wilkinson and Bloom[28] assigned the N^{14} 5.69-Mev level $J^\pi=1^+$ from a consideration of the strengths of the N^{14} $8.06\rightarrow5.69$ and $8.62\rightarrow5.69$ transitions and the slow-neutron threshold work of Marion *et al.*[55] The radiative width obtained[28] for the transition from the 0^+, N^{14} 8.62-Mev to the 5.69-Mev level is 0.7 ev. The quadrupole matrix element corresponding to this radiative width is $|M|^2=700$ Weisskopf units; therefore, the 5.69-Mev level is fixed as $J=1$. The radiative width of the N^{14} $8.06\rightarrow5.69$ transition, obtained from the absolute cross-section measurements of Seagrave[4] for the $C^{13}(p,\gamma)N^{14}$ reaction and an average of the γ-decay schemes obtained[28,53,56] for the 8.06-Mev level, is 0.56 ev with an estimated uncertainty of 20%. If the 5.69-Mev level is $J^\pi=1^-$, the $8.06\rightarrow5.69$ transition is $M1$ and has $|M|^2=2.0$ Weisskopf units. The distribution of $M1$ transition strengths in light ($A\leqslant20$) nuclei have a mean of ~0.15 Weisskopf unit with a spread of a factor of 20 either way needed to include 85% of the transitions.[23] Therefore, the radiative width of the $8.06\rightarrow5.69$ transition is not large enough to give a clear preference for $E1$ radiation as opposed to $M1$ radiation. In fact, if the $8.06\rightarrow5.69$ transition is $E1$ the $8.62\rightarrow5.69$ must be $M1$ and has $|M|^2=1.3$ Weisskopf units; so that either the $8.06\rightarrow5.69$ or the $8.62\rightarrow5.69$ transition has an $M1$ matrix element appreciably larger than the average value for light nuclei. It is concluded that the strengths of the $8.62\rightarrow5.69$ and $8.06\rightarrow5.69$ transitions are quite consistent with either parity assignment for the N^{14} 5.69-Mev level. If the 5.69-Mev level were 1^-, $s^4p^92s_{\frac{1}{2}}$ we should, in actual fact, be quite prepared for a large $M1$ matrix element connecting this state with its $T=1$ counterpart.

Marion *et al.*[55] observed a strong slow-neutron threshold at a deuteron energy of 0.422 Mev (corresponding to the N^{14} 5.69-Mev level) in the $C^{13}(d,n)N^{14}$ reaction. The yield of the reaction was observed to rise slowly above threshold suggested p-wave neutron emission. Marion *et al.*[55] envisaged a process in which the incoming deuteron is s-wave and the outgoing neutron is p-wave so that the final N^{14} state has even-parity. The large cross section at such a low deuteron energy certainly suggests s-wave capture; however, it seems reasonable that the reaction could proceed by a stripping mechanism—in which the orbital angular momentum of the neutron remains constant—with the capture of an s-wave proton by the s^4p^9 ground state of C^{13} into an $s^4p^92s_{\frac{1}{2}}$ state of N^{14}. Support for this conjecture is provided by the fact that the slow neutron threshold for the $C^{12}(d,n)N^{13}$ reaction corresponding to formation of the s^4p^82s, $\frac{1}{2}^+$, N^{14} 2.37-Mev level from the s^4p^8, 0^+, C^{12} ground state also rises slowly above threshold suggesting p-wave neutron emission.[55] In addition, the only other slow-neutron threshold observed by Marion *et al.*[55] in the $C^{13}(d,n)N^{14}$ reaction—studied for excitations in N^{14} from 5.5 to 8.8 Mev—corresponds to the $T=1$, s^4p^92s, 1^-, N^{14} 8.06-Mev level. It is concluded that the 5.69-Mev level could very well be $J^\pi=1^-$, and it is proposed as the $T=0$, 1^-, $s^4p^92s_{\frac{1}{2}}$ counterpart of the $T=1$, 1^-, N^{14} 8.06-Mev level.[57,¶]

It is perhaps worthwhile to point out that if the N^{14} 5.10-Mev level has $J^\pi=2^+$ rather than 2^-, it cannot be the missing $T=0$, s^4p^{10}, ${}^3D_2$ state expected[58,59] at 5-6 Mev excitation in N^{14}. This statement follows from a consideration of the γ decay of the 5.10-Mev level. Using the wave functions for the N^{14} ground state and 2.31-Mev level given by Visscher and Ferrell[59] and assuming the N^{14} 5.10-Mev level is the $T=0$, ${}^3D_2$ state of the s^4p^{10} configuration, Fallieros and Ferrell[60] calculated the $M1$ mean lifetime of the $5.10\rightarrow0$ transition to be 1.6×10^{-14} sec, with an $E2$ mean lifetime thirty times as great and a negligible branching ratio for the $5.10\rightarrow2.31$ cascade. This result is in serious contradiction with the lifetime limit ($\tau>3\times10^{-13}$ sec) obtained in the present work for the 5.10-Mev level, and with the known branching ratio (see Fig. 10) of the 5.10-Mev level. The formula for the $M1$ radiative width of the ground-state decay of the N^{14}, $T=0$, ${}^3D_2$ level, assuming that both it and the N^{14} ground state are pure s^4p^{10} states, is[61]

$$\Gamma_\gamma=3.6\times10^{-4}C_D{}^2E_\gamma{}^3 \text{ ev}, \tag{5}$$

where E_γ is in Mev and C_D is the coefficient of the ${}^3D_1$ part of the N^{14} ground-state wave function. From the known branching ratio of the N^{14} 5.10-Mev level, the lifetime limit on the 5.10-Mev level is found to correspond to a limit $\tau>4.5\times10^{-13}$ sec for the N^{14} $5.10\rightarrow0$ transition. If the 5.10-Mev level were the ${}^3D_2$ state, the experimental lifetime limit would combine with Eq. (5) to give $C_D{}^2<0.03$. However, the N^{14} ground state is known[59] to be predominantly ${}^3D_1$ so that the N^{14} 5.10-Mev level is ruled out as the ${}^3D_2$ state of the s^4p^{10}

[55] Marion, Bonner, and Cook, Phys. Rev. **100**, 847 (1955).
[56] Lehmann, Leveque, and Pick, Compt. rend. **243**, 743 (1956).

[57] Because of the proximity of the N^{14} 5.69- and 6.23-Mev levels and the similarity of their decay schemes, the comparison made by Wilkinson and Bloom (reference 28) of the isotopic-spin impurities of the $T=1$, 1^-, N^{14} 8.06-Mev level and its $T=0$ counterpart is practically unaffected by whether the 5.69- or 6.23-Mev level is the $T=0$, $J^\pi=1^-$ state in question.

¶ *Note added in proof.*—Perhaps the best evidence for an odd parity assignment for the 5.69-Mev level is given by the highly negative anisotropy of the decay to the 5.69-Mev level observed at $E_p=1.4$ Mev in $C^{13}(p,\gamma)N^{14}$ (see the note added in proof in Sec. IVC).

[58] J. P. Elliott, Phil. Mag. **1**, 503 (1956).
[59] W. Visscher and R. Ferrell, Phys. Rev. **107**, 781 (1957).
[60] Private communication from R. Ferrell (unpublished). We would like to thank Dr. Ferrell for communicating these calculations to us.
[61] Obtained from Eq. (6) of reference 42.

configuration even if the N^{14} ground-state wave function of Visscher and Ferrell is seriously in error, which is quite doubtful.

D. Electromagnetic Transitions

Because of the Δl selection rule, $M1$ transitions between the s^4p^92s and s^4p^91d configurations are forbidden. The C^{14} 7.35 → 6.72 transition was observed to be ⩾4 times as strong as the C^{14} 7.35 → 6.09 transition in spite of the fact that the 7.35 → 6.09 transition is energetically favored by a factor of 6.[17] This result is in agreement with the other evidence that the C^{14} 6.09- and 6.89-Mev levels are predominantly $s^4p^92s_{\frac{1}{2}}$, while the C^{14} 6.72- and 7.35-Mev levels are predominantly $s^4p^9d_{\frac{5}{2}}$. Likewise, the nonobservation of the N^{14} 8.06 → 5.10[28,53] and 9.50 → 5.69 transitions is consistent with the proposal of $s^4p^92s_{\frac{1}{2}}$ and $s^4p^9d_{\frac{5}{2}}$ as the predominant configurations of the N^{14} 5.69- and 8.06-Mev levels and the 5.10- and 9.50-Mev levels, respectively.

A striking result of the calculations of Elliott and Flowers[40] on the odd-parity states of mass 16 was how well the four lowest $T=1$, odd-parity states approximate to jj-coupling. To 96% in intensity these states were found to be the $J^\pi=0^-$, 1^-, 2^-, and 3^- levels expected from the $(p_{\frac{1}{2}}^{-1}2s_{\frac{1}{2}})$ and $(p_{\frac{1}{2}}^{-1}d_{\frac{5}{2}})$ configurations. On the other hand, the four lowest $T=0$, $J^\pi=0^-$, 1^-, 2^-, and 3^- levels of O^{16} seem to contain appreciable mixtures of other configurations in the predominant $(p_{\frac{1}{2}}^{-1}2s_{\frac{1}{2}})$ or $(p_{\frac{1}{2}}^{-1}d_{\frac{5}{2}})$ configurations.[40]

Under the assumption of extreme jj-coupling in the odd-parity states of both mass 14 and mass 16, the mass-14 levels from the configurations $(p_{\frac{1}{2}}2s_{\frac{1}{2}})$ and $(p_{\frac{1}{2}}d_{\frac{5}{2}})$ are directly related to the mass-16 levels from the configurations $(p_{\frac{1}{2}}^{-1}2s_{\frac{1}{2}})$ and $(p_{\frac{1}{2}}^{-1}d_{\frac{5}{2}})$. For extreme jj-coupling, then, Elliott[62] deduced that in mass 14 the $T=1$, 1^- $(p_{\frac{1}{2}}2s_{\frac{1}{2}})$ level lies below the $T=1$, 0^- $(p_{\frac{1}{2}}2s_{\frac{1}{2}})$ level, while in N^{14} the $T=0$, 0^- $(p_{\frac{1}{2}}2s_{\frac{1}{2}})$ level lies below the $T=0$, 1^- $(p_{\frac{1}{2}}2s_{\frac{1}{2}})$ level. Likewise, the $T=1$, 3^- $(p_{\frac{1}{2}}d_{\frac{5}{2}})$ level lies lower than the $T=1$, 2^- $(p_{\frac{1}{2}}d_{\frac{5}{2}})$ level, while the $T=0$, 2^- $(p_{\frac{1}{2}}d_{\frac{5}{2}})$ level lies lower than the $T=0$, 3^- $(p_{\frac{1}{2}}d_{\frac{5}{2}})$ level. In all four cases the separation is predicted to be 1–2 Mev; but, because of the rather strong dependence of this separation on the degree of intermediate coupling, these estimates are unreliable—especially for the $T=0$ levels. The relative positions of the odd-parity, and proposed odd-parity, states of mass 14 which have been discussed in this section are in good agreement with these qualitative estimates of Elliott.

The N^{14} ground state and 3.95-Mev level have been found to be the two lowest $T=0$, $J^\pi=1^+$, s^4p^{10} states of N^{14}.[58,59] Since an $E1$ transition between a $J^\pi=2^-$, $(p_{\frac{1}{2}}d_{\frac{5}{2}})$ state and a $J^\pi=1^+$, s^4p^{10} state is forbidden, the weakness of the N^{14} 9.50 → 0 and N^{14} 9.50 → 3.95 transitions (see Tables I and IV) gives support to the applicability of an extreme jj-coupling description of the odd-parity states under consideration.[63]

The unidentified $J^\pi=2^+$, $T=0$, $^3D_2$ state of the s^4p^{10} configuration cannot be formed from $(p_{\frac{1}{2}}^2)$, so that transitions to it from the $(p_{\frac{1}{2}}2s_{\frac{1}{2}})$ and $(p_{\frac{1}{2}}d_{\frac{5}{2}})$ configurations are forbidden. Therefore, the nonobservation of transitions from the N^{14} 1^- 8.06-Mev,[28,53] 2^- 9.50-Mev, and 3^- 8.90-Mev levels to any N^{14} state which could be this $^3D_2$ state (except possibly the N^{14} 6.44- or 7.02-Mev levels which are connected to the 8.90-Mev level by weak transitions), gives further evidence that the odd-parity states under consideration are fairly well described by jj coupling.

The results presented in this section suggest that perhaps it would be worth while to make a quantitative comparison of the predictions of jj coupling with the observed electromagnetic transitions connecting these N^{14} odd-parity states with each other and with the ground state configuration. Some preliminary calculations have been made and it appears that the strengths of those transitions reported in the present paper (Tables I and II) and those observed by others[8,28,53] are in fairly good agreement with extreme jj coupling assuming that the 4.91-, 5.69-, 5.10-, and 5.83-Mev levels are the 0^-, 1^-, 2^-, and 3^-, $T=0$ $(p_{\frac{1}{2}}2s_{\frac{1}{2}})$ and $T=0$ $(p_{\frac{1}{2}}d_{\frac{5}{2}})$ states in question.

E. Conclusions

Evidence has been presented that indicates the N^{14} 8.06-, 8.70-, 8.90-, and 9.50-Mev levels arise from the configurations s^4p^22s and s^4p^9d with the largest contribution being from the $(p_{\frac{1}{2}}2s_{\frac{1}{2}})$ configuration for the 8.06- and 8.70-Mev levels and from the $(p_{\frac{1}{2}}d_{\frac{5}{2}})$ configuration for the 8.90- and 9.50-Mev levels. From another point of view these states arise predominantly from binding a $2s_{\frac{1}{2}}$ or $d_{\frac{5}{2}}$ nucleon to the ground state of C^{13}. These two descriptions are connected by the fact that the C^{13} ground state is expected to be predominantly $s^4p_{\frac{3}{2}}^8p_{\frac{1}{2}}$. The analogs of these states in C^{14} are almost certainly those indicated in Fig. 15.

The identification of the $T=0$, $s^4p^92s_{\frac{1}{2}}$ and $s^4p^9d_{\frac{5}{2}}$ states of N^{14} is not as definite as the identification of their $T=1$ counterparts. However, it seems rather probable that the 4.91-, 5.69-, 5.10-, and 5.83-Mev levels are the 0^- and 1^- $s^4p^92s_{\frac{1}{2}}$ states and the 2^- and 3^- $s^4p^9d_{\frac{5}{2}}$ states, respectively.

If the odd-parity states are indeed well approximated by jj coupling, it would be expected that there would be a gap of 2–3 Mev or more between the four odd-

[62] Private communication from J. P. Elliott (unpublished).

[63] Although the forbiddenness of the $E1$ $(p_{1/2}d_{5/2}) \to (p^{10})$ transition gives a reasonable explanation for the weakness of the 9.50 → 3.95 transition, it can only be a partial explanation for the nonobservation of the 9.50 → 0 transition since the actual situation is certainly not expected to be close enough to jj-coupling to explain the extreme weakness of this transition ($\Gamma_\gamma < 7.6\times10^{-3}$ ev from the data of Table I). The extreme weakness of the 9.50 → 0 transition must be due, then, to chance cancellation in the actual intermediate coupling situation as well as to the vanishing of that part of the $E1$ matrix element corresponding to $(p_{1/2}d_{5/2}) \to (p^{10})$.

parity $T=0$ states and the next lowest odd-parity $T=0$ state, and similarly for the $T=1$ states (this energy gap being due to the spin-orbit splittings of the p and d shells). Therefore, a determination of the spin-parity assignments for the $T=0$ levels below 8 Mev in N^{14} (especially the 5.69- and 6.23-Mev levels) would be useful not only in identifying the four $T=0$ $(p_{\frac{1}{2}}2s_{\frac{1}{2}})$ and $(p_{\frac{1}{2}}d_{\frac{5}{2}})$ states, but also in estimating the purity of these states. Similarly, a definite determination of the spin-parity assignments of the $T=1$, N^{14} 9.16- and 10.43-Mev levels would be informative from this point of view.[64]

[64] *Note added in proof.*—The 9.16-Mev level has been shown to have even parity [Strassenburg, Hubert, Krone, and Prosser, Bull. Am. Phys. Soc. Ser. II, 3, 372 (1958)], and preliminary analysis indicates that the $T=1$ level at 10.43 Mev most probably has even parity also [Kashy, Perry, and Risser, Bull. Am. Phys. Soc. Ser. II, 4, 96 (1959)].

VI. ACKNOWLEDGMENTS

The authors are grateful to D. H. Wilkinson, D. E. Alburger, and especially J. P. Elliott for discussions concerning this work. They would like to thank I. W. Cole for the numerical evaluation of the Doppler-shift data. Thanks are also due the technical staff of the Brookhaven National Laboratory research Van de Graaff accelerator—especially R. A. Lindegren whose excellent and conscientious maintenance of the Van de Graaff and associated equipment was crucial to the completion of this work.

PHYSICAL REVIEW VOLUME 114, NUMBER 1 APRIL 1, 1959

Lifetimes of the First Excited 0+ States of Ca^{40} and Zr^{90}†

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(Received November 7, 1958)

The first excited states of Ca^{40} and Zr^{90} are 0+ states which decay to the 0+ ground state primarily by the emission of internal pairs or conversion electrons. These states have been excited by neutron inelastic scattering and their decay times have been observed by detecting the 0.51-Mev annihilation gamma rays as a function of time. The experimental method utilized a pulsed neutron source and the standard ring geometry often used for inelastic scattering measurements. Proton excitation of Ca^{40} in a different geometry was also used. To measure the lifetimes, the pulse-height spectra from a NaI(Tl) scintillation counter were recorded as a function of the delay time after the exciting pulse, and the intensity of the annihilation radiation was obtained from the area under the photopeak at 0.51 Mev. Selection of the time delays was made with the aid of either a time-to-pulse-height converter or a fast coincidence circuit. Mean lives for the first excited states of Ca^{40} and Zr^{90} were found to be $(3.4\pm0.2)\times10^{-9}$ sec and $(90\pm6)\times10^{-9}$ sec, respectively. Corresponding values of the reduced matrix elements ρ are 0.15 and 0.056.

I. INTRODUCTION

ELECTRIC-MONOPOLE transitions take place mainly by the emission of internal conversion electrons or electron-positron pairs. The nature of radiative transitions is such that competing gamma-ray transitions usually occur with much greater probability where both they and monopole transitions are possible. Therefore monopole transitions have usually been observed between two spin-zero levels. The cases of monopole transitions reported so far in the literature occur in the nuclei C^{12},[1] O^{16},[2] Ca^{40},[3–5] Ge^{70},[6] Ge^{72},[7] Zr^{90},[5,6,8,9] Cd^{114},[10] Pt^{196},[11] Bi^{212},[12] Po^{214},[13,14] U^{234},[15] and Pu^{238}.[15] The evidence with regard to most of these has recently been reviewed by Yuasa *et al.*[9]

In most cases the monopole transitions occur between a 0+ excited state and the 0+ ground state of even-even nuclei. Bi^{212} and Pt^{196} are exceptions. In Bi^{212} the transition is between the first and third excited states, for both of which the assignment of 0− is made; however, the evidence for this case is not yet very conclusive. The recent paper by Gerholm and Pettersson[11] gives evidence for the existence of an electric monopole transition in competition with an electric quadrupole-magnetic dipole mixture in a 2+-2+ transition in

† Work performed under the auspices of the U. S. Atomic Energy Commission.
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[1] L. I. Schiff, Phys. Rev. **98**, 1281 (1955).
[2] Devons, Goldring, and Lindsey, Proc. Phys. Soc. (London) **A67**, 134 (1954).
[3] Bent, Bonner, and McCrary, Phys. Rev. **98**, 1325 (1955).
[4] R. B. Day, Phys. Rev. **102**, 767 (1956).
[5] Kloepper, Day, and Lind, Bull. Am. Phys. Soc. Ser. II, **2**, 60 (1957).
[6] D. E. Alburger, Phys. Rev. **109**, 1222 (1958).
[7] M. Goldhaber and R. D. Hill, Revs. Modern Phys. **24**, 179 (1952).
[8] Johnson, Johnson, and Langer, Phys. Rev. **98**, 1517 (1955).
[9] Yuasa, Laberrigue-Frolow, and Feuvrais, J. phys. radium **18**, 498 (1957).
[10] H. T. Motz, Phys. Rev. **104**, 1353 (1956).
[11] T. R. Gerholm and B. G. Pettersson, Phys. Rev. **110**, 1119 (1958).
[12] Krisyouk, Sergeyev, Latyshev, and Vorobyov, Nuclear Phys. **4**, 579 (1957).
[13] C. D. Ellis and G. H. Aston, Proc. Roy. Soc. (London) **A129**, 180 (1930).
[14] R. H. Fowler, Proc. Roy. Soc. (London) **A129**, 1 (1930).
[15] Perlman, Asaro, Harvey, and Stephens, Bull. Am. Phys. Soc. Ser. II, **2**, 394 (1957).