Study of Unbound Levels in N^{14} by the $C^{12}(He^3,p\gamma)N^{14}$ Reaction

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(Received 29 May 1967)

The 8.49-, 8.96-, and 9.17-MeV unbound levels of N^{14} have been studied by particle-γ angular-correlation measurements for the $C^{12}(He^3,p\gamma)N^{14}$ reaction at 8.92 MeV bombarding energy. These levels were found to γ decay in competition with proton decay with the width ratios $\Gamma_p/\Gamma_\gamma=3.7\pm1.1$, 4.09 ± 0.49, and 10 ± 3, respectively. The spin and parity of the N^{14} 8.96-MeV level have been definitively established as $J^\pi=5^+$. The γ widths of the $E2$ transitions from the 8.96- and 8.49-MeV levels have been compared with shell-model predictions. In addition, an unusual result was obtained for the N^{14} 7.03-MeV level. While at $E_{He^3}=5.11$ MeV, the $m=0$ substate of this level was predominantly populated, it was found that at $E_{He^3}=8.92$ MeV the $|m|=1$ substates were strongly populated. The latter has been interpreted as due to $s=1$ transfer in a possible heavy-particle stripping reaction.

I. INTRODUCTION

In a previous paper, Gorodetzky *et al.*[1] studied the properties of the bound states of N^{14}, excited in the reaction $C^{12}(He^3,p\gamma)N^{14}$, by particle-$\gamma$ coincidence experiments at four bombarding energies: 4.62, 4.90, 5.11, and 5.46 MeV. Detenbeck, Armstrong, Figuera, and Marion,[2] by a careful investigation of the $C^{13}(p,\gamma)N^{14}$ reaction, observed three midget resonances corresponding to the N^{14} 8.49-, 8.96-, and 9.13-MeV unbound levels. Carlson[3] found that the 8.49- and 8.96-MeV levels, excited by the $B^{10}(Li^6,d)N^{14}$ reaction, γ decay in competition with proton decay. This last result was confirmed by Gallmann, Haas, and Balaux[4] for the N^{14} 8.96-MeV level excited by the $C^{12}(He^3,p\gamma)N^{14}$ reaction at $E_{He^3}=10$ MeV.

The 5.5-MeV Van de Graaff accelerator at the Centre de Recherches Nucléaires at Strasbourg, has recently been equipped with a doubly ionized helium beam. With the beam energies now available, the highly excited N^{14} unbound levels were studied by particle-γ angular correlation measurements of the reaction $C^{12}(He^3,p\gamma)N^{14}$, where the particles were detected close to 180°.[5] Some further data were also obtained on the lower-lying levels of N^{14}.

II. EXPERIMENTAL PROCEDURE

In a preliminary study, particle spectra were recorded at $(He^3)^{++}$ bombarding energies between 8.5 and 10.5 MeV. To obtain particle spectra with good resolution, a semiconductor counter (resistivity 2200 Ω cm) was placed at 172°, the mean angle of detection for the subsequently used annular counter, and thin self-supporting carbon targets of 15 $\mu g/cm^2$ thickness were used. Good yield was obtained at a bombarding energy of 8.92 MeV; this energy was chosen for the present experiments. The corresponding particle spectrum is shown in Fig. 1 for a collected charge of 400 μC. The proton groups feeding the bound and unbound states of N^{14} in the excitation region of 5 to 10 MeV are indicated. The excitation energies of the N^{14} levels are taken from Carlson.[3] Other peaks observed in the spectrum correspond to the elastically scattered He^3 beam and to particle groups from population of excited states in C^{11} from the reaction $C^{12}(He^3,\alpha)C^{11}$, and to the ground state of N^{13} from the reaction $C^{12}(He^3,d)N^{13}$. Particle groups with weak intensity, arising from the reactions O^{16}-$(He^3,\alpha)O^{15}$, and $O^{16}(He^3,He^3)O^{16}$, due to oxygen impurity in the targets, are also evident. A careful energy calibration was made for this spectrum. A full width at half-maximum of ~3.5 channels corresponds to a resolution of ~25 keV.

Experimental details of the angular-correlation measurements have already been given in previous papers.[1,4,6] We used the target chamber described in previous experiments[4,6]; the particles were detected close to 180° in an annular silicon semiconductor counter (resistivity 1000 Ω cm), placed at 4 cm from the target. The γ rays were detected in a 5×6-in. NaI crystal, whose front face was 28.5 cm from the target. For all the experiments, the intensity of the $(He^3)^{++}$ beam was approximately 0.05 μA. Good coincidence yield was obtained using self-supporting carbon targets of 70 $\mu g/cm^2$ thickness. The resolution of the particle counter was ~90 keV. The particle-γ coincidences were registered in a multidimensional 20 000-channel analyzer (200 channels for the γ ray spectra and 100 channels for the particle spectra). The coincidence spectra were measured twice at 5 angles: 0°, 30°, 45°, 60°, and 90°. At each angle a charge of 300 μC was collected. These coincidence spectra were added together in order to have good statistics for determining the γ-ray decay schemes of the levels. The γ-ray spectra shown in this paper were obtained by this means.

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[1] S. Gorodetzky, R. M. Freeman, A. Gallmann, and F. Haas Phys. Rev. **149**, 801 (1966).
[2] R. W. Detenbeck, J. C. Armstrong, A. S. Figuera, and J. B. Marion, Nucl. Phys. **72**, 552 (1965).
[3] R. R. Carlson, Phys. Rev. **148**, 991 (1966).
[4] A. Gallmann, F. Haas, and N. Balaux, Phys. Rev. **151**, 735 (1966).
[5] A. E. Litherland and A. J. Ferguson, Can. J. Phys. **39**, 788 (1961).
[6] S. Gorodetzky, R. M. Freeman, A. Gallmann, F. Haas, and B. Heusch, Phys. Rev. **155**, 1119 (1967).

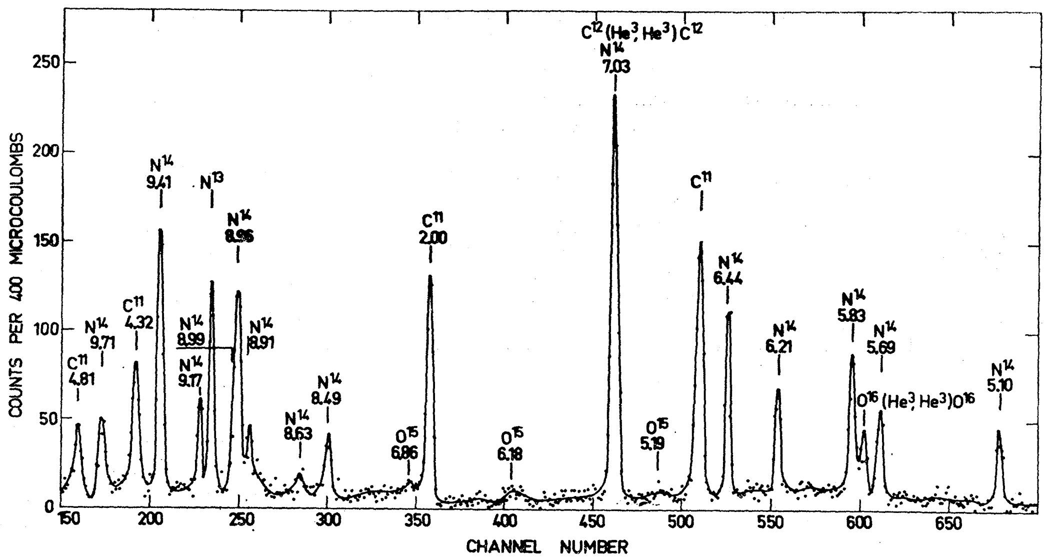

FIG. 1. Particle spectrum for $(He^3)^{++}$ incident on an C^{12} target (15 $\mu g/cm^2$ thickness) at a bombarding energy of 8.92 MeV. The semiconductor counter was placed at $\sim 172°$. The particle groups are labeled by the excitation energy (MeV) and nature of the final nucleus. The peaks are due mainly to elastic scattering and the $C^{12}(He^3,p)N^{14}$, $C^{12}(He^3,\alpha)C^{11}$, $C^{12}(He^3,d)N^{13}$ reactions, but some small peaks from oxygen impurity, i.e., elastic scattering and the reaction $O^{16}(He^3,\alpha)O^{15}$, are also present

III. EXPERIMENTAL RESULTS

The angular correlations were fitted by a minimum-χ^2 calculation with a series of Legendre polynomials of the form

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

The coefficients a_2 and a_4 of the angular correlations for the N^{14} bound levels are listed in Table I, and have not been corrected for the finite size of the NaI crystal. The appropriate attenuation coefficients are $Q_2=0.97$ and $Q_4=0.91$.

The angular correlations depend on the mixing ratios of the de-excitation γ rays and also, for the $C^{12}(He^3,p\gamma)$-N^{14} reaction presently studied, on a population parameter describing the relative population $P(0)/P(1)$ of the $m=1$ and 0 magnetic substates of the N^{14} levels.

The experimental angular correlations were analyzed using the minimum-χ^2 computer program previously described.[1]

TABLE I. Coefficients of the Legendre polynomials of the angular correlations for the N^{14} bound levels at 8.92-MeV beam energy.

Level (MeV)	γ-ray energy (MeV)	a_2	a_4
5.10	2.79	$+0.43\pm0.13$	-0.88 ± 0.17
	5.10	$+0.02\pm0.05$	-0.31 ± 0.05
5.69	3.38	-0.18 ± 0.07	
	5.69	$+0.17\pm0.10$	
5.83	2.79	$+0.66\pm0.14$	-0.42 ± 0.16
	5.83	$+0.79\pm0.09$	$+0.18\pm0.09$
6.21	3.90	-0.05 ± 0.05	
	6.21	-0.07 ± 0.06	
6.44	2.49	$+0.53\pm0.05$	-0.39 ± 0.06
	6.44	$+0.59\pm0.04$	-0.45 ± 0.07
7.03	7.03	-0.66 ± 0.03	-0.20 ± 0.02

From the p-γ angular correlations of the bound levels of 5.10-, 5.69-, 5.83-, and 6.21-MeV, at the present bombarding energy of 8.92 MeV, no information can be added to our previous results[1] obtained at different, lower bombarding energies. The p-γ angular correlations of the 6.44-MeV level will be considered in the study of the 8.96-MeV level.

At 8.92-MeV He^3 beam energy, the 7.03-MeV level was strongly excited. An accurate angular correlation for the ground-state transition [Fig. 2(a)] has been measured, with the following results:

$$a_2=-0.66\pm0.03\,,$$
$$a_4=-0.20\pm0.02\,.$$

The corresponding solutions for the mixing ratio $\delta=E2/M1$ of the 7.03-MeV γ rays are

$$\delta=+0.7\pm0.1 \quad \text{or} \quad \delta=+1.1\pm0.1\,.$$

At $E_{He^3}=5.11$ MeV, the angular correlation of the 7.03-MeV γ rays [Fig. 2(b)] leads to the following values of the Legendre-polynomial coefficients:

$$a_2=-1.02\pm0.03\,,$$
$$a_4=+0.21\pm0.04\,.$$

These last values are in agreement with our previous measurements.[1] The positive a_4 values obtained in our previous work[1] at the bombarding energies 4.62, 4.90, 5.11, and 5.46 MeV all led to a single solution for the mixing ratio, i.e., $\delta=+0.6\pm0.2$, in good agreement with the solution $\delta=+0.7\pm0.1$, which fits the angular correlation of the 7.03-MeV γ rays at $E_{He^3}=8.92$ MeV.

The coefficients a_2 and a_4 should lie near the segment AB of the triangle indicated in Fig. 3, where A, B, and

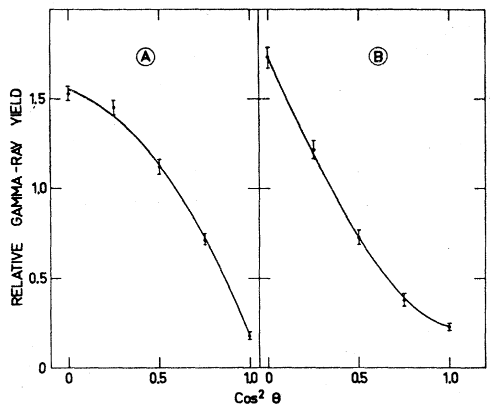

FIG. 2. Angular correlations for the ground-state transition from the 7.03-MeV level. The correlations (A) and (B) were obtained at beam energies of 8.92 and 5.11 MeV, respectively.

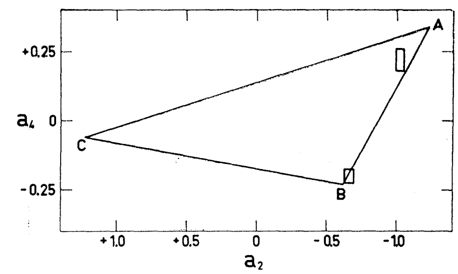

FIG. 3. Triangle bounding the region of a_2 and a_4 values theoretically possible for the correlation of the 7.03-MeV γ ray, spin $2 \rightarrow 1$ transition, assuming a mixing ratio $\delta = +0.70$. Each vertex corresponds to 100% population of $|m| = 0$, 1, and 2 substates in the order ABC. The experimental values for the correlations are shown as rectangles and lie near vertices A and B at beam energies 5.11 and 8.92 MeV, respectively.

C correspond to 100% population of the $|m| = 0$, 1, and 2 magnetic substates, respectively, of the 7.03-MeV level. The vertices of the triangle were calculated assuming $\delta = +0.70$. The a_2 and a_4 values measured at beam energies of 5.11 and 8.92 MeV are plotted with their errors as rectangles in Fig. 3; these points lie near vertex A, $m = 0$ substate strongly populated, and near vertex B, $|m| = 1$ substates strongly populated, respectively.

At $E_{He^3} = 5.11$ MeV, the strong population of the $m = 0$ substate of the N^{14} 7.03-MeV level is not surprising, because it has been found that for all the excited bound states of N^{14} with nonzero spin a strong preference exists for the $m = 0$ substate.[1] Thus the result obtained at $E_{He^3} = 8.92$ MeV seems quite remarkable. At this bombarding energy 100% population of the $|m| = 1$ substates is needed to account for the measured angular correlation of the 7.03-MeV level, while for the other levels $P(0)/P(1)$ is less than 1. If the reaction mechanism contributing to the excitation of the N^{14} 7.03-MeV level is predominantly compound nuclear, it would not be expected that any one substate would be preferentially populated for all bombarding energies. The strong populations of the substate $m = 0$ at $E_{He^3} = 5.11$ MeV and of the substates $|m| = 1$ at $E_{He^3} = 8.92$ MeV indicate that at the two bombarding energies, direct interaction is contributing significantly to the formation of the 7.03-MeV level. The strong excitation of the 7.03-MeV level at $E_{He^3} = 8.92$ MeV argues in favor of a heavy-particle stripping process for two reasons. Firstly, the effect due to normal stripping should be small at 180°, while the effect due to heavy-particle stripping is near a maximum.[7] Secondly, the 7.03-MeV level, which belongs to a core-excited configuration, could only be formed by normal stripping through the $p_{3/2}{}^6 p_{1/2}{}^2$ minor component of the C^{12} ground state.[8] Indeed, if the C^{12} ground state were a pure $p_{3/2}{}^8$ configuration, the 7.03-MeV state could only be formed by a heavy-particle stripping process where the outgoing proton comes from the C^{12} core. If the mechanism is heavy-particle stripping, the strong population of the $|m| = 1$ substates seems to show $s = 1$ transfer,[9] i.e., spin flip, between the intrinsic spins of the incident He^3 particle and the outgoing proton from the C^{12} core. A further study of the reaction mechanism concerning the 7.03-MeV level between 4 and 11 MeV bombarding energies is planned.

The 8.96-MeV Level

A spectrum of γ rays in coincidence with protons to the triplet of levels at 8.91-, 8.96-, and 8.99-MeV is shown in Fig. 4, where the dashed line is the random-coincidence spectrum. The triplet is unresolved in the annular counter; however, γ rays of 6.44, 2.52, 2.31, and 1.64 MeV seen in the spectrum can be attributed to a cascade through the 6.44-MeV level and there is no evidence for any other mode of decay. Only the 8.96-MeV member of the triplet, has such a decay scheme[2] and thus the γ rays from the triplet shown in Fig. 4 can be assigned to the 8.96-MeV level.

Two angular correlations have been measured for the 8.96-MeV level for the following transitions and γ ray energies:

(i) $8.96 \rightarrow 6.44$ transition:

$$2.40 \text{ MeV} \leqslant E_\gamma \leqslant 2.72 \text{ MeV};$$

(ii) $6.44 \rightarrow 0$ transition:

$$5.52 \text{ MeV} \leqslant E_\gamma \leqslant 6.76 \text{ MeV}.$$

The correlations, shown in Figs. 5(a) and 5(b), were fitted to Legendre polynomial expansions yielding

(i) $a_2 = +0.46 \pm 0.06$, $a_4 = -0.28 \pm 0.07$;

(ii) $a_2 = +0.45 \pm 0.05$, $a_4 = -0.29 \pm 0.07$.

[7] M. El Nadi and M. El Khishin, Proc. Phys. Soc. (London) **73**, 705 (1959).

[8] D. Kurath, Phys. Rev. **101**, 216 (1956).

[9] L. J. B. Goldfarb, Nucl. Phys. **57**, 4 (1964).

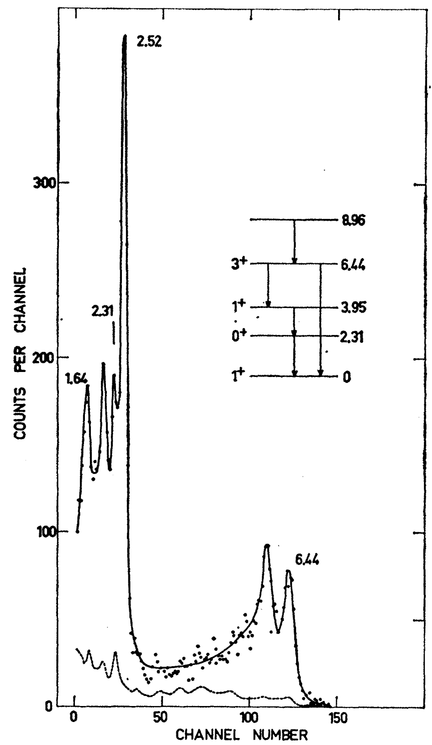

FIG. 4. Spectrum of γ rays from the $C^{12}(He^3,p\gamma)N^{14}$ reaction in coincidence with protons to the triplet of levels 8.91, 8.96, and 8.99 MeV, obtained at an $(He^3)^{++}$ bombarding energy of 8.92 MeV. The γ-ray peaks, which are marked by their energies in MeV, are due to a cascade through the 6.44-MeV level. An estimation of the number of random coincidences is shown by the dashed line. A total charge of 1895 μC was collected to obtain this spectrum.

For the angular correlation of the $8.96 \rightarrow 6.44$ transition, a contribution of the 2.49-MeV γ rays, due to the $6.44 \rightarrow 3.95$ transition, was subtracted. To obtain the correction at each angle, we measured the two p-γ angular correlations for the 6.44-MeV level, $6.44 \rightarrow 3.95$ and $6.44 \rightarrow 0$. From these identical correlations of spin $3 \rightarrow 1$ $E2$ transitions, shown in Figs. 5(c) and 5(d), we knew at each angle the relative intensity of the 6.44- and 2.49-MeV transitions.

Minimum-χ^2 fits to the correlation of the $8.96 \rightarrow 6.44$ transition are shown in Fig. 6 with spin assignments $J=3$ for the 6.44-MeV level and $J=1$, 2, 3, 4, and 5 for the 8.96-MeV level. The value $J=0$ can be excluded by the anisotropy of the angular correlation. Only spins $J=3$ and 5 for the 8.96-MeV level lead to good fits to the measured angular correlation. The χ^2 value obtained for $J=6$ and pure octupole radiation is 13, and thus $J=6$ is eliminated. A simultaneous fit to the correlations of the 2.52- and 6.44-MeV transitions, taking the latter to be pure E_2, is shown in Fig. 7 with spin assignments $J=3$ and 5 for the 8.96-MeV level. The spin assignment for the N^{14} 8.96-MeV level is definitively $J=5$. From Fig. 6, the value of the mixing ratio for the $8.96 \rightarrow 6.44$ MeV transition is found to be $\delta=-0.01\pm0.06$, indicating that the 2.52-MeV γ-ray transition is a pure $E2$ or $M2$ transition. (The sign of δ corresponds to an $M3/E2$ mixture.) With the value $J=5$ for the 8.96-MeV level, the spins of the levels in the cascade $8.96 \rightarrow 6.44 \rightarrow 0$ form a monotonic sequence $(5 \rightarrow 3 \rightarrow 1)$; the transitions are basic and so, as expected,[10,11] we find that the angular correlations are identical.

The protons feeding the 8.96-MeV level are only partially in coincidence with γ rays, i.e., some of the decay is by proton emission. The ratio Γ_p/Γ_γ could be obtained by

(i) Measuring the ratio R_p of the number of protons feeding the 8.96-MeV level to the number of protons feeding the 6.44-MeV level. By using the particle spectrum of Fig. 1, we obtain

$$R_p=1.11\pm0.09.$$

As can be seen in this spectrum, the triplet of levels 8.91, 8.96, and 8.99 MeV, is not totally resolved. A fit of three Gaussian distributions plus a constant background was made in the region of channel numbers 240–260, in order to obtain an accurate value of the number of protons feeding the 8.96-MeV level.

(ii) Measuring the ratio R_γ of the number of 6.44-MeV γ rays in coincidence with protons feeding the

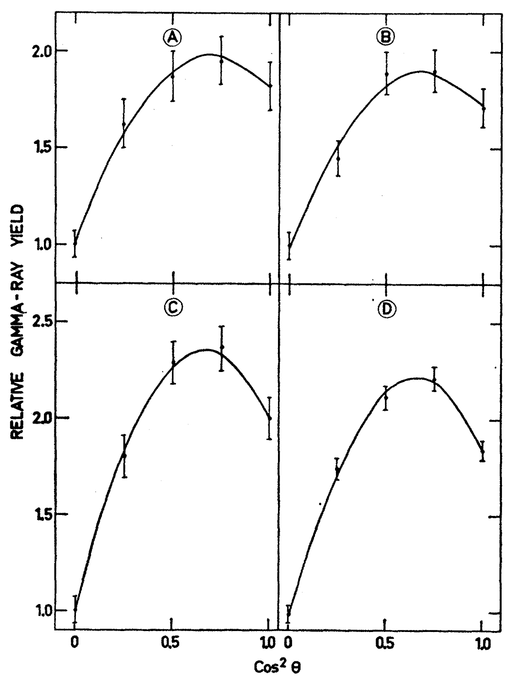

FIG. 5. Angular correlations for the reaction $C^{12}(He^3,p\gamma)N^{14}$ for the 8.96- and 6.44-MeV levels of N^{14}. The correlations are for a bombarding energy of 8.92 MeV; (A) is for the $8.96 \rightarrow 6.44$ transition and (B) is for the $(8.96) \rightarrow 6.44 \rightarrow 0$ transition; (C) is for the $6.44 \rightarrow 3.95$ transition $(3^+ \rightarrow 1^+$ $E2$ transition); (D) is for the 6.44-MeV ground state transition $(3^+ \rightarrow 1^+$ $E2$ transition). The lines are the correlations according to the coefficients given in Table I and in the text.

[10] J. Weneser and D. R. Hamilton, Phys. Rev. **92**, 321 (1953).
[11] S. Raboy and V. E. Krohn, Phys. Rev. **98**, 24 (1955).

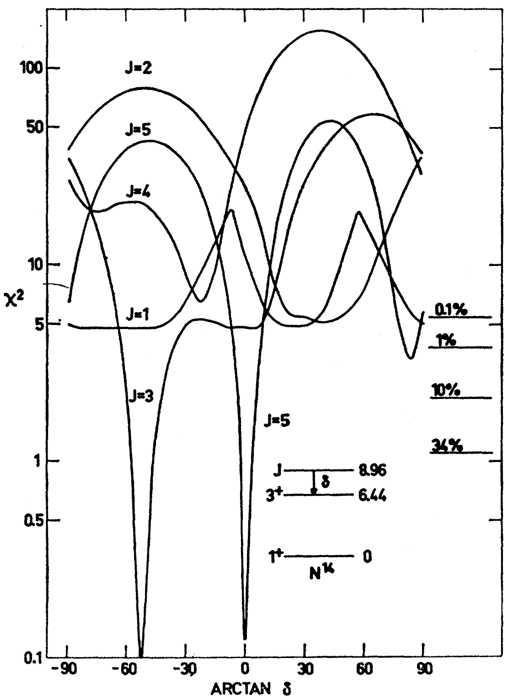

FIG. 6. Minimum χ^2 analysis of the correlation of the $8.96 \to 6.44$ transition of N^{14}, trying values $J=1$–5 for the spin of the 8.96-MeV level.

6.44-MeV level to the 6.44-MeV γ rays in coincidence with the protons feeding the 8.96-MeV level, corrected for the angular correlations. We found

$$R_\gamma = 4.59 \pm 0.23.$$

By combining these two results we obtained

$$\Gamma_p/\Gamma_\gamma = (R_p \times R_\gamma) - 1 = 4.09 \pm 0.49.$$

For the 8.96-MeV level Detenbeck *et al.*,[2] using the $C^{13}(p,\gamma)N^{14}$ reaction, reported the following result:

$$\omega[\Gamma_p \times \Gamma_\gamma / (\Gamma_p + \Gamma_\gamma)] = 3 \times 10^{-3}\ \text{eV}, \quad \omega = 11/4.$$

This result, combined with the measured width ratio Γ_p/Γ_γ of the present experiment, leads to the following widths for the 8.96-MeV level:

$$\Gamma_\gamma = (1.36 \pm 0.21) \times 10^{-3}\ \text{eV},$$
$$\Gamma_p = (5.56 \pm 0.87) \times 10^{-3}\ \text{eV}.$$

The strengths of the $E2$ or $M2$ $8.96 \to 6.44$ transition are (in Weisskopf units[12])

$$E2 \text{ transition: } |M(E2)|^2 = 8.0 \pm 1.5,$$
$$M2 \text{ transition: } |M(M2)|^2 = 153 \pm 24.$$

[12] D. H. Wilkinson, in *Nuclear Spectroscopy*, edited by F. Ajzenberg-Selove (Academic Press Inc., New York, 1960), Part B, p. 852.

TABLE II. Résumé of results for the N^{14} 8.96-MeV and 8.49-MeV unbound levels.

Level (MeV)	J^π	Γ_p (10^{-3} eV)	Γ_γ (10^{-3} eV)	Transition (MeV)	$\|M(E2)\|^2$ (W.u.)
8.96	5^+	5.56 ± 0.87	1.36 ± 0.21	$8.96 \to 6.44$	8.5 ± 1.5
8.49	$4^{-\text{a}}$	21.0 ± 9.8	5.6 ± 2.0	$8.49 \to 5.10$	8 ± 3

ᵃ Reference 2.

An $M2$ transition being ruled out as unreasonably strong, we conclude that the $8.96 \to 6.44$ transition is a $5^+ \to 3^+$ $E2$ transition (see Table II).

The 8.49-MeV Level

A spectrum of γ rays in coincidence with protons to the 8.49-MeV level is shown in Fig. 8. Gamma rays of 5.10, 3.39, 2.79, and 2.31 MeV can be seen from the cascade through the 5.10-MeV level. In agreement with Carlson,[3] we found that there is no evidence for any other mode of decay. The dashed line in Fig. 8 is the random-coincidence spectrum. Angular correlations for the 8.49-MeV level were obtained with the following results:

$$8.49 \to 5.10 \text{ transition: } a_2 = +0.39 \pm 0.13, \quad a_4 = -0.15 \pm 0.15,$$
$$5.10 \to 0 \text{ transition: } a_2 = +0.13 \pm 0.10, \quad a_4 = -0.07 \pm 0.11.$$

We were not able to determine a unique value of J and spins $J=1$–4 for the 8.49-MeV level lead to acceptable fits. For the χ^2 analysis we have taken into account

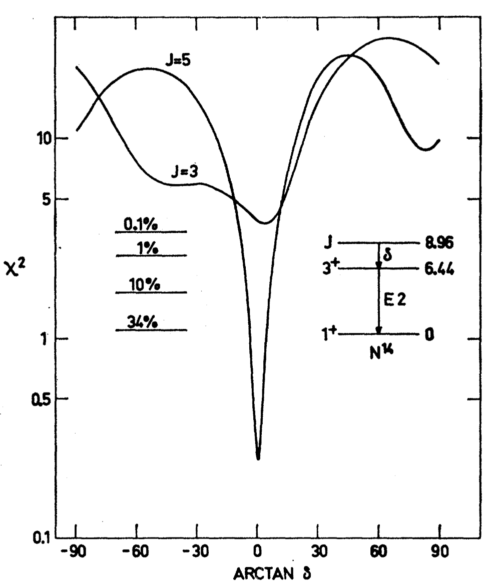

FIG. 7. Simultaneous minimum χ^2 analysis of the 2.52- and 6.44-MeV transitions of the decay of the 8.96-MeV level of N^{14}. The minimum χ^2 values have been calculated for the remaining possible spin assignments to the 8.96-MeV level, $J=3$ or 5 and varying the mixing ratio of the 2.52-MeV transition. The 6.44-MeV transition is an $E2$ transition.

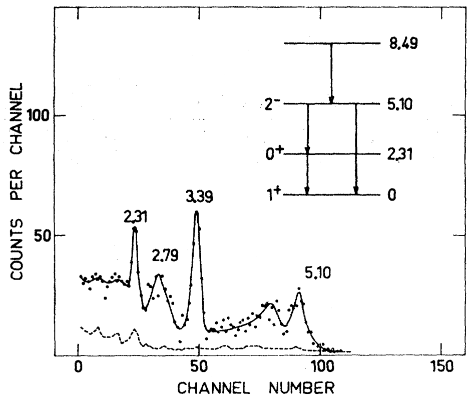

FIG. 8. Spectrum of γ rays from the $C^{12}(He^3,p\gamma)N^{14}$ reaction in coincidence with protons to the 8.49-MeV level, obtained at an $(He^3)^{++}$ bombarding energy of 8.92 MeV. The γ-ray peaks, which are marked by their energies in MeV, are due to cascade through the 5.10 -MeV level. An estimation of the number of random coincidences is shown by the dashed line. A total charge of 1895 μC was collected to obtain this spectrum.

the known $E1$, $M2$, $E3$ character of the $5.10 \rightarrow 0$ transition.[1] For each of these J values, we established the mixing ratio of the $8.49 \rightarrow 5.10$ transition. For $J=4$, which is the only value consistent with the experimental data of Detenbeck *et al.*, we find

$$+0.18 \geqslant \delta \geqslant -0.19 \quad (\delta = M3/E2).$$

The width ratio for the 8.49-MeV level has been measured in a similar manner to that described in the analysis of the 8.96-MeV level, with the following result:

$$\Gamma_p/\Gamma_\gamma = 3.7 \pm 1.1.$$

For the 8.49-MeV level, Detenbeck *et al.* obtained

$$\omega[\Gamma_p\Gamma_\gamma/(\Gamma_p+\Gamma_\gamma)] = 10^{-2}\ \text{eV}, \quad \omega = 9/4.$$ [12a]

This last result, combined with the width ratio, leads to the following widths:

$$\Gamma_\gamma = (5.6 \pm 2.0) \times 10^{-3}\ \text{eV},$$
$$\Gamma_p = (21.0 \pm 9.8) \times 10^{-3}\ \text{eV}.$$

With the assumption $\Gamma_p \gg \Gamma_\gamma$, Detenbeck *et al.* fixed the $E2$ character of the $8.49 \rightarrow 5.10$ transition and the negative parity of the 8.49-MeV level. Taking into account the width ratio measured in our experiment, this assignment remains true because Γ_γ varies only slightly with Γ_p. The γ width of the 8.49-MeV level corresponds to the following $E2$ transition strength of the $8.49 \rightarrow 5.10$ transition $(4 \rightarrow 2)$:

$$|M(E2)|^2 = 8 \pm 3.$$

The $M2$ transition strength would be

$$|M(M2)|^2 = 142 \pm 52.$$

To check the consistency of the width-ratio results, it had to be shown that, e.g., for the two bound levels of 6.44- and 5.10-MeV, the ratio R_p' of the intensities of the protons feeding the 6.44- and the 5.10-MeV levels is equal to the ratio R_γ' of the intensities of the 6.44- and 5.10-MeV γ rays in coincidence with the corresponding proton groups feeding the levels considered. We found

$$R_p' = 2.6 \pm 0.3 \quad \text{and} \quad R_\gamma' = 2.7 \pm 0.15.$$

The γ-ray intensities were corrected this time for photofractions, total efficiencies, and angular correlations.

The 9.17-MeV Level

Gamma rays of about 9 MeV were observed in the coincidence γ-ray spectra. They were attributed to the ground-state transition of the N^{14} 9.17-MeV level. A careful examination of the coincidence spectra, of the particle spectra at $E_{He^3} = 8.92$ MeV and at neighboring bombarding energies has shown that the N^{14} 9.13-MeV level is very weakly excited at $E_{He^3} = 8.92$ and so, does not contribute to the 9 MeV γ-ray transition. An anisotropy given by $a_2 = +0.70 \pm 0.20$ was measured for the 9.17-MeV ground-state transition. The error of about 30% for the a_2 coefficient is due to the low number of counts in the coincidence spectra. The angular correlation can only be fitted by spin values $J=1$ or 2 for the 9.17-MeV level. This state has been extensively studied,[13–16] and a spin-parity assignment $J^\pi = 2^+$ has been attributed to this level. To determine the widths ratio Γ_p/Γ_γ of the 9.17-MeV level, the intensities of the particle groups corresponding to the 9.17- and 6.44-MeV levels were compared as were the intensities of the 9.17- and 6.44-MeV γ rays in the coincidence γ-ray spectra. The ratio, taking into account corrections for photofractions, total efficiencies, branching ratios, and angular correlations, was found to be $\Gamma_p/\Gamma_\gamma = 10 \pm 3$. Hanna and Meyer-Schutzmeister[17] have measured the total level width $\Gamma = 77 \pm 12$ eV and the γ width $\Gamma_\gamma = 8.7 \pm 1.5$ eV, with a corresponding width ratio $\Gamma_p/\Gamma_\gamma = 8 \pm 2$, in reasonable agreement with the ratio measured in this experiment.

[12a] *Footnote added in proof.* D. F. Hebbard has drawn our attention to a difficulty in the interpretation of the $C^{13}(p,\gamma)$ results for the 8.49-MeV state. In the event that $\omega \neq 9/4$, one obtains the following values for the γ width of the 8.49-MeV state

Assumed J of 8.49-MeV level	ω	Γ_γ in 10^{-3} eV
1	3/4	1.9±0.7
2	5/4	3.1±1.1
3	7/4	4.3±1.6

The values of δ for these different possible J values would be:

$J=1$ $(1 \rightarrow 2)$ All values of δ possible

$J=2$ $(2 \rightarrow 2)$ $+0.23 \geqslant \delta \geqslant -\infty$ $(\delta = E2/M1)$

$J=3$ $(3 \rightarrow 2)$ $-0.75 \geqslant \delta \geqslant -0.27$ or $\delta \leqslant -2.75$ $(\delta = E2/M1)$.

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IV. DISCUSSION

Particle decay of the 8.49-MeV ($J^\pi=4^-$) and 8.96-MeV ($J^\pi=5^+$) levels requires $l=4$ and $l=5$ proton waves, respectively. The penetrability of such high-angular-momentum proton waves is sufficiently low to account, in a great part, for the very small proton widths of these levels, i.e., $\Gamma_p=(5.56\pm0.87)\times10^{-3}$ eV for the 8.96-MeV level and $\Gamma_p=(21.0\pm9.8)\times10^{-3}$ eV for the 8.49-MeV level. The following proton reduced widths have been obtained: $(4.08\pm0.64)\times10^{-3}$ eV ($\sim1.3\times10^{-3}$ of the Wigner limit) for the 8.96-MeV level and $(2.6\pm1.2)\times10^{-3}$ eV ($\sim8.5\times10^{-4}$ of the Wigner limit) for the 8.49-MeV level.

The 8.96-MeV Level

The spin-parity assignment $J^\pi=5^+$ for the 8.96-MeV level suggests immediately that it is the $(d_{5/2})^2$, $J^\pi=5^+$, $T=0$ level predicted by True[18] to lie at an excitation energy of 9.32 MeV. This level was first observed in the $C^{12}(\alpha,d)N^{14}$ reaction at an excitation energy of 9.0±0.2 MeV.[19,20] The 8.96-MeV level decays to the 6.44-MeV level by an $E2$ transition. We now compare the determined experimental γ width of this level with the prediction of the shell model. We adopt the common approximation of regarding C^{12} as a closed subshell.

For the 8.96-MeV state ($J^\pi=5^+$) we take the wave function of True:

$$\psi(5)=C_{5/2^5}\psi(d_{5/2})^2.$$

The 6.44-MeV level ($J^\pi=3^+$) has a wave function of the form

$$\psi(3)=C_{1/2,5/2^3}\psi(s_{1/2}d_{5/2})+C_{3/2,3/2^3}\psi(d_{3/2})^2 +C_{3/2,5/2^3}\psi(d_{3/2}d_{5/2})+C_{5/2,5/2^3}\psi(d_{5/2})^2.$$

We have calculated the strength of the $E2$ transition connecting these two levels with the following result:

$$\Lambda(E2)=2[C_{5/2,5/2^5}(C_{1/2,5/2^3}+0.3536C_{3/2,5/2^3} +0.5774C_{5/2,5/2^3})]^2\times\gamma^{-2}(1+2\beta)^2.$$

The relation between the transition strength $\Lambda(E2)$ and the radiative width $\Gamma(E2)$ is given by Warburton and Pinkston.[21] The square of the radial integral $\langle r^2\rangle^2$, appearing in the expression for $\Lambda(E2)$, has been calculated using harmonic oscillator radial wave functions which have a radial fall-off of the form, $\exp[-\frac{1}{2}\gamma r^2]$. Following Visscher and Ferrell,[22] we take $\gamma^{-1/2}=1.68$ F. The quantity β which appears in the expression for $\Lambda(E2)$ is the effective-charge parameter of the weak-coupling approximation such that proton and neutron have charge $(1+\beta)e$ and βe, respectively. The evidence from neighboring nuclei is that β is approximately 0.5. Numerical results for the $E2$ radiative width have been calculated for two different sets of wave functions. The first is extreme j-j coupling, for which we found

$$\Gamma(E2)=0.52\times10^{-3}\text{ eV}.$$

The second set is that of True,[18] for which we obtained

$$\Gamma(E2)=0.60\times10^{-3}\text{ eV}.$$

The maximum value of $\Gamma(E2)$ is obtained by using the wave function of True for the 6.44-MeV level with the magnitude of the $(d_{5/2})^2$ amplitude increased by a factor of 1.25. We found

$$\Gamma(E2)=0.70\times10^{-3}\text{ eV}.$$

However, this last result remains a factor of 2 smaller than our experimental width i.e., $\Gamma(E2)=(1.36\pm0.21)\times10^{-3}$ eV. An increase in β would bring the theoretical predictions into better agreement with experiment but a value $\beta=0.9$ is needed for a complete accord. The discrepancy is almost certainly due to the inadequacies of our assumption of an inert $(p_{3/2})^8$ core.

The 8.49-MeV Level

Detenbeck *et al.*[2] assigned the dominant core-excited configuration $(p_{3/2})^{-1}(p_{1/2})^2(d_{5/2})$ to the 8.49-MeV level ($J^\pi=4^-$). Assuming this configuration and spin parity, we calculated the radiative width of the $E2$ transition connecting the 8.49-MeV level and the 5.10-MeV level [dominant configuration: $(p_{1/2})(d_{5/2})$]. The following result was obtained:

$$\Gamma(E2)=1.91\times10^{-3}\text{ eV}.$$

This value is to be compared to our experimental width, i.e.,

$$\Gamma(E2)=(5.6\pm2.0)\times10^{-3}\text{ eV}.$$

V. CONCLUSIONS

By particle-γ angular correlation measurements, we have studied the N^{14} 8.49-, 8.96-, and 9.17-MeV unbounds levels. A spin-parity assignment $J^\pi=5^+$ has been established for the 8.96-MeV level. Very small total widths have been found for the 8.49- and 8.96-MeV unbound levels. The experimental γ widths of the $E2$ transitions from these levels are about a factor of 2 or 3 larger than simple shell-model predictions.

ACKNOWLEDGMENT

We should like to thank Dr. E. K. Warburton for useful comments on this manuscript.

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