Gamma Decay of the Lowest $T=\frac{3}{2}$ State of ^{13}N†

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γ-ray transitions are observed in the reaction $^{12}C(p,\gamma)^{13}N$ from the sharp $T=\frac{3}{2}$ resonance at $E_x=15.07$ MeV in ^{13}N to the ground state and to higher excited states. For the ground-state transition, $\Gamma_p\Gamma_\gamma/\Gamma=5.5\pm0.8$ eV. The angular distribution of this transition confirms $J^\pi=\frac{3}{2}^-$ for the $T=\frac{3}{2}$ state and gives an amplitude ratio of $E2/M1=-0.095\pm0.07$, in agreement with theory in sign and magnitude. The widths for decay to the ground and excited states are compared with shell-model predictions, and with the analog β transitions in the decay of ^{13}B.

I. INTRODUCTION

VERY narrow, highly excited levels have been found[1,2] in ^{13}C and ^{13}N by the analogous reactions $^{11}B(^3He,p)^{13}C$ and $^{11}B(^3He,n)^{13}N$, at excitation energies above 15 MeV. The levels in ^{13}N have also been observed[3–5] as resonances in the elastic scattering of protons by ^{12}C. Because of their narrow widths and the fact that they are located near the energies expected from comparison with the levels of ^{13}B, it is assumed that these states are $T=\frac{3}{2}$ levels in ^{13}N. The allowed β decay[6] of ^{13}B to the ground and second excited states of ^{13}C requires $J^\pi=\frac{1}{2}^-$ or $\frac{3}{2}^-$ for the ^{13}B ground state and its analogs. The $\frac{3}{2}^-$ assignment is favored by the double-stripping reaction[7] $^{11}B(t,p)^{13}B$.

The present experiment studies the radiative decay of the lowest $T=\frac{3}{2}$ level in ^{13}N formed as a resonance in the capture reaction $^{12}C(p,\gamma)^{13}N$. The results are compared with predictions of pure j-j and intermediate coupling models, and with the ft values for the β decay of ^{13}B.

II. EXPERIMENTAL TECHNIQUES AND RESULTS

Self-supporting carbon targets were bombarded by protons accelerated in the Stanford FN tandem accelerator. The resonance occurs at a bombarding energy of about 14.2 MeV. The γ spectra from the reaction were observed with a 24×24-cm NaI detector inside a plastic anticoincidence shield. The pileup pulses in the spectra were suppressed with a fast discriminator and coincidence circuitry.[8] The energy resolution for 15 MeV γ rays was approximately 5.5%. γ spectra were also observed with a 25-cm^3 germanium detector. The targets were prepared by spraying alco-dag on microscope slides with an artist's air brush mounted in a lathe.[9] Targets of nominal thicknesses of 12 and 52 keV at $E_p=14.2$ MeV were used for the observations with the NaI detector, and a target of nominal thickness 17 keV for the spectra obtained with the Ge counter. The targets were mounted on aluminum frames and placed in a glass chamber. After passing through the target, the beam was stopped about 2 m behind the target in a Faraday cup lined with lead. The current entering the Faraday cup was integrated by a Dymec voltage-to-frequency converter and a scaler.

The resonance corresponding to the narrow $T=\frac{3}{2}$ state of ^{13}N was first investigated with the NaI detector

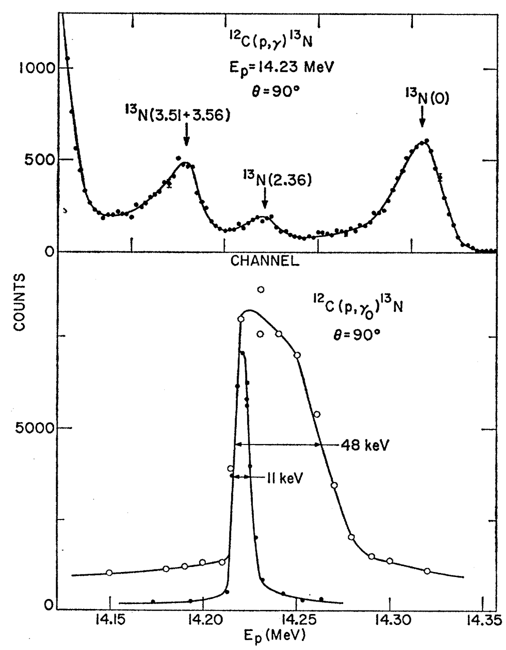

FIG. 1. γ spectrum at the $E_x=15.07$-MeV resonance, and excitation functions in the region near the resonance.

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at 90° with respect to the incident beam. The front face of the NaI crystal was approximately 35 cm from the target. The γ rays from the target passed through a lead collimator of length 12.7 cm, whose center was filled with Li_2CO_3-loaded paraffin to reduce the neutron background. The neutron background was further reduced by placing paraffin slabs (total thickness = 12 cm) between the target and the collimator.

The γ spectra were stored in a 512-channel analyzer. Counts in the NaI crystal which were unaccompanied by a pulse in the anticoincidence shield were stored in the first half of the analyzer (accepted spectrum), and those that were accompanied by an anticoincidence pulse were routed into the second half of the analyzer (rejected spectrum). Approximately one-third of the pulses fall in the rejected spectrum. The upper portion of Fig. 1 shows a typical accepted spectrum obtained on resonance with a 12-keV target. The highest-energy peak at 15.1 MeV corresponds to de-excitation γ rays to the ground state of ^{13}N. The next peak at about 12.7 MeV may correspond to transitions to the 2.36-MeV state of ^{13}N, but it may also include γ rays from the decay of the 12.7-MeV state in ^{12}C produced in the inelastic scattering reaction $^{12}C(p,p')^{12}C^*$. The third peak at about 11.5 MeV may include contributions from decay to both of the levels at 3.51 and 3.56 MeV in ^{13}N (see Fig. 2). The sharp rise at energies below the 11.5-MeV group is due to neutron-capture γ rays produced in the crystal assembly and its environment. The lower half of Fig. 1 shows 90° excitation functions of the ground-state transition for the targets of two thicknesses.

Angular distributions of the γ rays were measured with the front face of the crystal 49 cm from the target and with the collimator and paraffin replaced by a Li_2CO_3-paraffin cylinder of length 14.3 cm. The angular distributions for transitions to the ground state and to the combined second and third excited states, measured

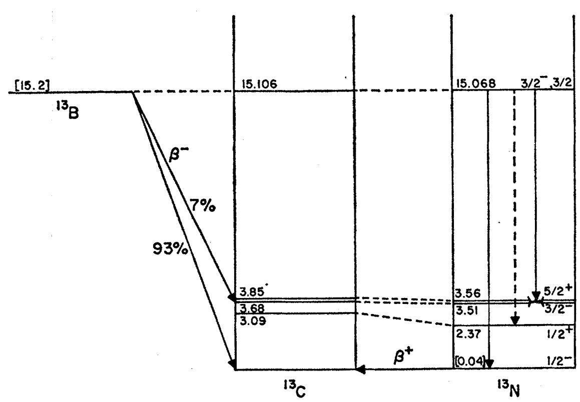

Fig. 2. Partial level scheme of the mass-13 nuclei. Energies and spin-parity assignments are taken from Refs. 1 and 2 and from F. Ajzenberg-Selove and T. Lauritsen, in *Nuclear Data Sheets*, compiled by K. Way *et al.* (U. S. Government Printing Office, National Academy of Sciences—National Research Council, Washington, D. C.), NRC No. 61-5, 6-91.

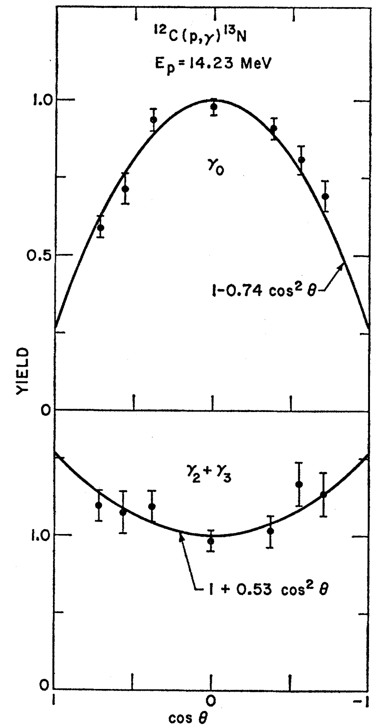

Fig. 3. Angular distributions of the γ's to the ground state of ^{13}N, and to the unresolved second and third excited states. The nonresonant yield has been subtracted.

with the thicker target, are shown in Fig. 3. Each point at each angle was obtained by subtracting a spectrum obtained just below resonance from the on-resonance spectrum. The data were then corrected for the solid angle of the detector. Least-square Legendre polynomial fits to the data give angular distributions of $P_0-(0.66\pm0.09)P_2$ for the transition to the ground state, and $P_0+(0.30\pm0.10)P_2$ for that to the combined second and third excited states. The angular distribution of the 12.7-MeV γ rays was not measured, because the group is rather weakly resonant. If this group corresponds to decay of the $\frac{3}{2}^-$, $T=\frac{3}{2}$ state to the $\frac{1}{2}^+$ first excited state of ^{13}N, and if the transition is pure $E1$, the angular distribution would be $P_0-\frac{1}{2}P_2$.

The measured angular distributions allow the ratios of the γ-decay widths to the various states to be determined from the 90° yields. For the combined second and third excited states, the result is $(\Gamma_{\gamma_2}+\Gamma_{\gamma_3})/\Gamma_{\gamma_0}=0.84\pm0.08$. For the first excited state we obtain $\Gamma_{\gamma_1}/\Gamma_{\gamma_0}<0.14$.

The quantity $\Gamma_p\Gamma_\gamma/\Gamma$ for the ground-state transition was determined from a 90° yield curve, measured with the thicker target, and from the ground-state angular distribution. Since the width of the resonance is very small compared with the thick-target thickness, the thick-target yield formula was employed:

$$\Gamma_p\Gamma_\gamma/\Gamma=2\epsilon Y/\lambda_p^2\omega.$$

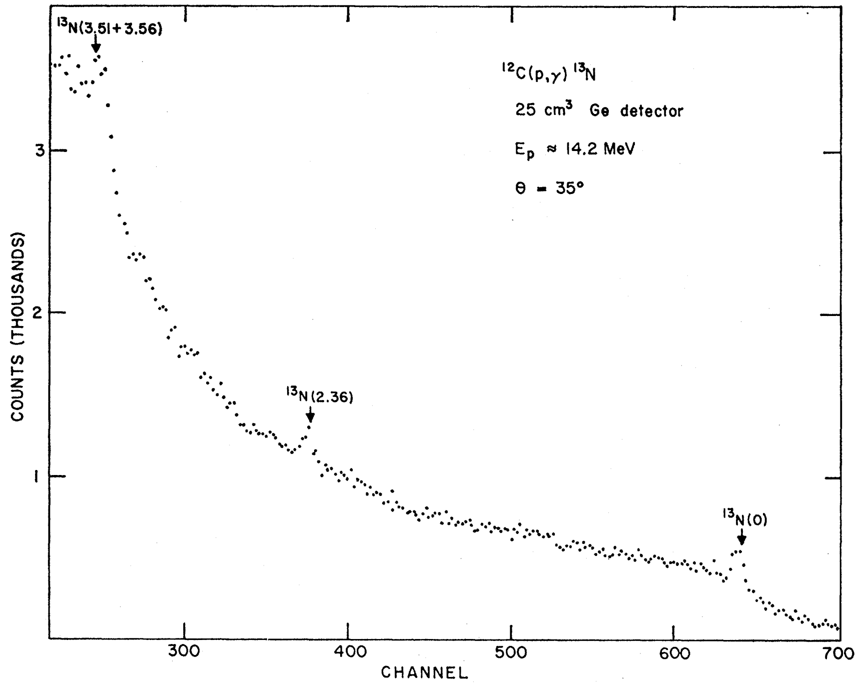

FIG. 4. γ spectrum at the $E_x = 15.07$-MeV resonance, obtained with a 25-cm³ lithium-drifted germanium detector.

In the above, Y is the step in the yield function, expressed as the total number of ground-state γ's per incident proton, ϵ is the stopping power of the target, and λ_p is the proton wavelength in the center-of-mass system. The statistical factor is $\omega=(2J+1)/(2i+1)(2s+1)$, where i and s are the spins of the projectile and target, and J is the spin of the compound resonance.

The total yield Y was determined by correcting the observed number of γ counts for the efficiency of the detector, by integrating this corrected yield over all solid angles (taking account of the angular distribution), and then by normalizing the integrated yield to the total proton flux. In determining the detector efficiency, a correction was made for the small number of γ rays ($\approx 2\%$) which pass through the crystal without interaction. It was assumed that all of the remaining γ rays which reach the front face of the crystal appear in either the accepted or rejected spectrum. The fraction of γ's which were stopped in the material between the target and the crystal was determined by runs in which the paraffin slabs and the Li_2CO_3-loaded paraffin plug in the collimator were removed. The total count in the accepted spectrum was found by fitting the peak in the spectrum with a standard shape determined from the $^{11}B(p,\gamma)^{12}C$ reaction, with the aid of the Stanford PDP-7 computer system. It was assumed that the shape of the γ spectrum is flat at energies below the half-energy point; an error of $\pm 4\%$ has been included in the results to account for possible deviations from this assumption. The $^{11}B(p,\gamma)^{12}C$ reaction was also used to determine the fraction of γ's that appear in the rejected spectrum. Combining all these steps we find the yield to be $Y=(6.1\pm 0.6)\times 10^{-9}$ γ's/proton. With[10] $\epsilon=(0.61\pm 0.02)\times 10^{-15}$ eV cm², $\lambda_p=8.23\times 10^{-13}$ cm, and $\omega=2$, we obtain

$$\Gamma_p\Gamma_\gamma/\Gamma=5.5\pm 0.8 \text{ eV}.$$

Since $\Gamma_p/\Gamma<1$, we take $\Gamma_\gamma>4.7$ eV. If we combine the result above with the recently determined result[11] $\Gamma_p/\Gamma=0.20\pm 0.025$, we obtain

$$\Gamma_\gamma=27\pm 5 \text{ eV}.$$

[*Note added in proof.* A value of 25 ± 7 eV has been obtained for the width of the analog state in ^{13}C by Peterson.[11a]]

The γ rays were also observed with a 25-cm³ coaxial lithium-drifted germanium detector, with the result shown in Fig. 4. The detector was positioned at 35° with respect to the incident beam, and it subtended an angle of about 30°. A target of 17 keV nominal thickness was used, and the run was monitored by the NaI crystal, to insure that the beam energy remained on resonance. The run lasted about 55 h, with an average current of about 60 nA. The same three peaks that were prominent in the NaI spectra appear in the Ge spectrum, and no additional structure was observed. Because of the Doppler broadening of the peaks it was still not possible to resolve the γ's to the first excited state of ^{13}N from the γ rays from inlastic scattering of the 12.73-MeV

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TABLE I. Parameters of γ transitions from the $T=\frac{3}{2}$, $J^\pi=\frac{3}{2}^-$ state in ^{13}N to lower $T=\frac{1}{2}$ levels.

Final state		Γ_γ(eV)				A_2[a]		δ[b]	
E_x(MeV)	J^π	Theor.[c]	Theor.[d]	Expt.	Expt.[e]	Theor.	Expt.	Theor.[f]	Expt.
0	$\frac{1}{2}^-$	39	27	>4.7	27±5	−0.75	−0.66±0.09	−0.167	−0.095±0.07
2.365	$\frac{1}{2}^+$	⋯	⋯	⋯	<4.5	0.50[g]			
3.51	$\frac{3}{2}^-$	48	10 }	>4.0	23±5	{ 0.51 }	0.30±0.10	{ +0.074	
3.56	$\frac{5}{2}^+$	⋯	⋯ }			{ 0.10[g] }		{	

[a] Coefficient in $P_0+A_2P_2$.
[b] Amplitude ratio of $E2$ and $M1$ radiation.
[c] J. G. Ginocchio, quoted in Ref. 4.
[d] Reference 13.
[e] Present result combined with Ref. 11.
[f] For $\langle r^2\rangle=7fm^2$, Ref. 14.
[g] For pure $E1$ radiation.

state of ^{12}C. The γ's to the 3.51- and 3.56-MeV states of ^{13}N also remained unresolved.

III. DISCUSSION

The angular distribution of the ground-state γ rays confirms the $J^\pi=\frac{3}{2}^-$ assignment for the resonant state, since the choice of $\frac{1}{2}^-$ would require an isotropic angular distribution. The multipolarities of the transitions can then be identified as $M1,E2$ to the ground and to the second excited states, and $E1,(M2)$ to the first and third excited states.

If the ground-state transition were pure $M1$, its angular distribution would be $P_0-\frac{1}{2}P_2$. The observed coefficient of P_2 gives an $E2/M1$ intensity ratio of either $0.009_{-0.008}^{+0.018}$ or 2.0 ± 0.5. The latter value would be unreasonably large for a radiation width equal to 27 eV as deduced above. The Weisskopf estimate for the $E2$ radiation is 1 eV. The signs of the $E2$ and $M1$ matrix elements are opposite, according to the convention of Poletti and Warburton.[12]

A similar analysis of the angular distribution to the second excited state is complicated by the possible presence of the unresolved γ's to the third excited state.

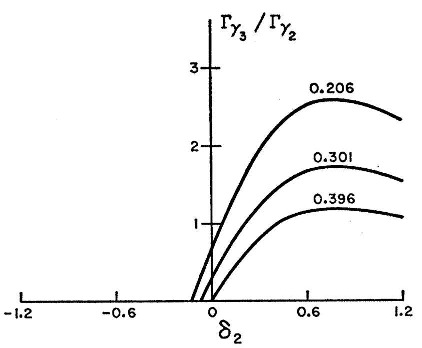

FIG. 5. Relationship between the ratio of widths for decay to the third and second excited states, and the $E2/M1$ mixing ratio for the second excited state. The curves are labeled by the coefficient A_2 in the angular distribution $1+A_2P_2(\cos\theta)$; the experiment yields $A_2=0.30\pm0.10$.

The $E1$ angular distribution to the third excited state is expected to be of the form $P_0-\frac{1}{10}P_2$. The measured angular distribution then implies a relationship between the $E2/M1$ mixing coefficient for the second excited state, and the ratio of γ widths to the second and third excited states. This relationship is shown in Fig. 5. It is expected that transitions to states out of the p shell (i.e., to positive parity levels) should be weak, as is evidently true for the transition to the first excited state. The angular distribution is consistent with a small $E2/M1$ mixing ratio for the second excited state, and a small width for the $E1$ transition to the third excited state.

The results of this experiment are compared with theoretical predictions in Table I. For the transitions within the p shell, the predicted radiation widths fall within the allowed experimental ranges. The widths of Cohen and Kurath[13] agree with the experimental result $\Gamma_{\gamma_2}/\Gamma_{\gamma_0}<1$. Their value for the ground-state transition would agree with our experimental result if $\Gamma_p/\Gamma=0.20$ in agreement with the measurement of Adelberger *et al.*[11] The predicted[14] $E2/M1$ mixing ratio δ is in good agreement with experiment. A value of $\langle r^2\rangle=7\,fm^2$ was used in calculating the $E2$ matrix element. Better agreement could be obtained by using a smaller value of $\langle r^2\rangle$. The agreement in sign as well as magnitude adds to the examples in which such agreement has been observed in the p shell.[15]

The spin portion of the $M1$ matrix element connecting the initial $(J^\pi,T)=(\frac{3}{2}^-,\frac{3}{2})$ state and the ground $(\frac{1}{2}^-,\frac{1}{2})$ and second excited $(\frac{3}{2}^-,\frac{1}{2})$ states of ^{13}N may be estimated from the experimental ft values[6] for the β decay of ^{13}B to the analogous states in ^{13}C. If the orbital portion of the matrix element may be neglected, it is then possible to predict the corresponding $M1$ radiation widths. The expression used for this comparison is

$$\Lambda(M1)=\tfrac{1}{8}(g_p-g_n)^2\frac{(T_fT_{f_3}{}^{\gamma}10\,|\,T_iT_{i_3}{}^{\gamma})^2}{(T_fT_{f_3}{}^{\beta}11\,|\,T_iT_{i_3}{}^{\beta})^2}\langle\sigma\rangle^2,$$

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TABLE II. Estimates of the transition strengths to the ground and second excited states of ^{13}N, by comparison with the β decay of ^{13}B, and from a *j-j* coupling model of ^{13}N.

Final state	β decay		*j-j* model		
J^π, T	Expt. log ft[a]	Γ_γ(eV)	log ft	Γ_γ(no l)	Γ_γ(with l)
$\frac{1}{2}^-$, $\frac{1}{2}$	4.01	29.8	4.12	23.3	18.5
$\frac{3}{2}^-$, $\frac{1}{2}$	4.53	4.06	4.64[b]	3.18[b]	13.2[b]

[a] Reference 6.
[b] See text for description of states.

where g_p and g_n are the proton and neutron gyromagnetic ratios, and the isospin-coupling Clebsch-Gordan coefficients refer to the initial and final nuclear states involved in the γ and β transitions. The reduced transition strengths are related to the corresponding experimental quantities[16,17] by

$$\Gamma_\gamma(\text{eV})=(2.76\times10^{-3})[E_\gamma(\text{MeV})]^3\Lambda(M1),$$

and $ft=4390/\langle\sigma\rangle^2$ sec. The ^{13}B β-decay ft values yield ^{13}N γ widths of 29.8 eV for the ground-state transition, and 4.06 eV for the second-excited state transition. (See Table II.) The former width is in reasonable agreement with the expected value, but the latter width would then be in disagreement with the observed branching ratio, unless the $E1$ transition to the unresolved third excited state is very much stronger than the other transition out of the p shell to the first excited state.

In order to investigate the validity of neglecting the orbital portion of the $M1$ matrix elements, these matrix elements were calculated from a simple *j-j* coupling model. The initial $(\frac{3}{2}^-,\frac{3}{2})$ state was formed from the configuration $(p_{3/2}^{-1}p_{1/2}^{-2})$, and the ground $(\frac{1}{2}^-,\frac{1}{2})$ state from the configuration $(p_{1/2}^{-3})$. The second excited $(\frac{3}{2}^-,\frac{1}{2})$ state was also formed from the configuration $(p_{3/2}^{-1}p_{1/2}^{-2})$, but here there are two possible states, corresponding to the couplings of the two $p_{1/2}$ holes to give $(J,T)=(0,1)$ and $(1,0)$. The $E1$ matrix elements for transitions to the first and third excited states vanish in this model, since the initial state cannot be connected to states outside the p shell by a single-particle transition. The results, both including and neglecting the orbital contribution, are shown in Table II. The full $M1$ matrix element for the ground-state transition is proportional to $1-(g_p-g_n)$, in which the first term represents the orbital contribution. Neglecting the orbital contribution overestimates the γ width by about 25%. For the $(\frac{3}{2}^-,\frac{1}{2})$ state, the absolute value of the maxtrix element and the ratio of the orbital and spin parts are very sensitive to the ratio of the two components in the $(\frac{3}{2}^-,\frac{1}{2})$-state vector. Reasonable agreement with our observed γ branching ratio and with the ^{13}B β decay is obtained by assigning an amplitude of 0.496 to the component in which the $p_{1/2}$ holes are coupled to $(J,T)=(0,1)$. Although the *j-j* coupling model is no substitute for a careful intermediate-coupling calculation, it shows that care must be exercised in interpreting the comparison of the $M1$ and β matrix elements, and that the observed branching ratio to the ground and second excited states is not necessarily inconsistent with the ^{13}B β-decay branching ratio.

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