TABLE I. The percentages of the energy-weighted sum rule.

E_x (MeV)	$E1$, $T=1$	$E2$, $T=0$	$E2$, $T=1$	$E3$, $T=0$	$E4$, $T=0$	$E5$, $T=0$	$E6$, $T=0$	$E7$, $T=0$
0–3.5		5		10	8	2		
3.5–5				4		3		
5–10	3	14		39		34		26
10–15	25	65			47		38	
15–20	50	20	11	10	12	37	29	21
20–25	10	7	13	24	10	35	35	29
25–30			16	20	12	26	20	46

multipole strength is fragmented in accord with recent theoretical results.[9-11]

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Mirror γ Decays in ^{13}C and ^{13}N†

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We have measured the γ-ray branching ratios of the lowest $T=\frac{3}{2}$ levels in ^{13}C and ^{13}N, and the absolute strength of the γ_0 transition in ^{13}N. The mirror electromagnetic selection rule is obeyed by the $M1$ (γ_0 and γ_2) transitions. However the $E1$ (γ_1) transitions exhibit a surprisingly large charge asymmetry. Charge-dependent differences in the radial wave functions do not account for a similar asymmetry in strong $T=\frac{1}{2}\rightarrow T=\frac{1}{2}$ $E1$ transitions in mass 13.

Isovector γ-ray decays between corresponding levels of mirror nuclei are expected to be of equal strength.[1] This follows from two assumptions—that the nuclear levels involved obey charge symmetry, and that the electromagnetic current contains only isoscalar and isovector components. Hence a precise experimental comparison of the reduced strengths of mirror $\Delta T=1$ transitions can reveal asymmetries caused either by a failure of exact symmetry in the nuclear wave functions, or by the existence of an exotic (isotensor) electromagnetic current.

The mirror selection rule for $\Delta T=1$ electromagnetic transitions is not well verified.[2] Blin-Stoyle has used the $T=\frac{3}{2}\rightarrow T=\frac{1}{2}$ $M1$ transitions in ^{13}C and ^{13}N to derive an upper limit of ~10% for the ratio of the isotensor to isovector amplitudes.[3] We have improved upon previous data[4,5] concerning the mirror $\Delta T=1$ γ decays in mass 13 by significantly increasing the precision of the comparison of the ground-state and second-excited-state $M1$ transition strengths. We have also extended the comparison to the $E1$ transitions to the first excited states and the $E2$ component of the ground-state transitions.

The absolute strength of the γ_0 transition from the $T=\frac{3}{2}$ level in ^{13}N was determined by combining a $^{12}C(p, \gamma_0)^{13}N$ resonance-yield measurement of $\Gamma_{p0}\Gamma_{\gamma0}/\Gamma$ with a previous measurement[6] of Γ_{p0}/Γ. The $^{12}C(p, \gamma_0)^{13}N$ resonance-yield data shown in Fig. 1 were obtained by bombarding a 1.7-mg/cm^2 natural carbon target with a proton beam from the University of Washington FN tandem Van de Graaff accelerator. γ rays were detected at $\theta_\gamma=125°$ in a 25-cm×25-cm-diam NaI spectrometer with a plastic anticoincidence shield. The solid curve shown in Fig. 1 is a Monte Carlo calculation[7] of the resonance yield that includes the discontinuous energy loss of protons in the carbon targets.

Since the angular distribution of the decay γ rays from an isolated $J=\frac{3}{2}$ level must have the form $a_0P_0(\cos\theta)+a_2P_2(\cos\theta)$, the step in the total thick-target resonance yield can be obtained from data taken at $\theta_\gamma=125°$, where $P_2(\cos\theta)$ vanishes. The absolute photopeak efficiency of the detector for 15.1-MeV γ rays was determined by use of a coincidence observation of tagged γ rays from the decay of the 15.1-MeV level in ^{12}C, which was assumed to have $\Gamma_{\gamma0}/\Gamma=(88.2\pm2.1)\%$.[8,9] This $J=1$ level was populated in the reaction $^{10}B(^3He, p\gamma)^{12}C$ with protons detected at 0° so that the γ-ray angular distribution was also of the form $a_0'P_0(\cos\theta)+a_2'P_2(\cos\theta)$. The $^{12}C(p, \gamma_0)^{13}N$ resonance-yield measurement and the calibration were done consecutively with use of the same experimental arrangement. Only the target and beam were changed.

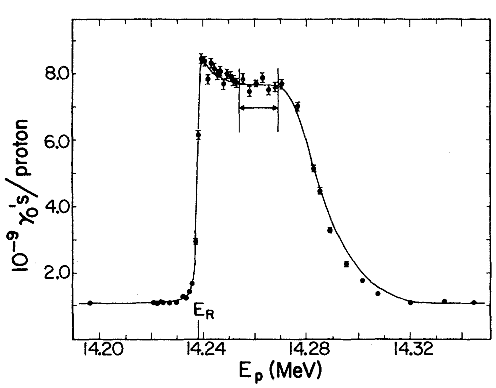

FIG. 1. Resonance yield for the reaction $^{12}C(p,\gamma_0)^{13}N$ at $\theta_\gamma=125°$. Only statistical errors are shown. There is an additional uncertainty of ±3% in the NaI efficiency. The energy scale comes from the nominal accelerator calibration.

On the basis of the "plateau" region of the resonance-yield curve (delineated by vertical bars in Fig. 1), the step in the total thick-target yield corresponds to $(6.83\pm0.22)\times10^{-9}$ γ_0's per incident proton for a pure natural carbon target of infinite thickness. The precision of our result makes it useful as a calibration standard for absolute γ-ray detection efficiencies. This yield corresponds to $\Gamma_{p0}\Gamma_{\gamma0}/\Gamma=5.79\pm0.20$ eV, on the basis of a stopping power of 30.75 ± 0.31 keV/(mg/cm^2).[10] Combining this result with a previous measurement[6] of Γ_{p0}/Γ yields $\Gamma_{\gamma0}(^{13}N)=24.5\pm1.5$ eV). This should be compared with $\Gamma_{\gamma0}(^{13}C)=23.3\pm2.7$ eV.[11] Our value of Γ_{γ_0} should not be significantly affected by interference between the resonance and the background since $\sigma_R/\sigma_B\approx230$ and $E1$ or $E2$ backgrounds cannot produce interference in a_0. Our data at 125° measure a_0 since the resonance angular distribution was found to have a negligible a_1 coefficient.

From $^{12}C(p, \gamma_0)^{13}N$ angular-distribution data taken below, above, and on the $^{13}N(T=\frac{3}{2})$ resonance, we deduce a value of 0.013 ± 0.005 for the $E2/M1$ intensity ratio in the ground-state transition. This differs from the value of 0.026 ± 0.005 for the corresponding transition in ^{13}C (Ref. 11).

The relative transition strengths to the first and second excited states were obtained from a coincidence measurement using the reactions $^{11}B(^3He, p\gamma)^{13}C$ and $^{11}B(^3He, n\gamma)^{13}N$. The protons or neutrons were detected at 0° and the γ rays were detected at $\theta_\gamma=125°$. The data were recorded on magnetic tape event by event and sorted later to obtain the final γ-ray spectra shown in Fig. 2. The smooth curves are least-squares fits using the 15.1-MeV line shape obtained from the $^{10}B(^3He, p\gamma)^{12}C$ data. Our results for the relative transition strengths in ^{13}C and ^{13}N are summarized in Table I. In ^{13}N, the group labeled γ_1 could contain an unresolved contribution from γ rays following isospin-forbidden proton decay to $^{12}C(12.71)$, and hence the $T=\frac{3}{2}\to(\frac{1}{2},\frac{1}{2})$ strength in ^{13}N is given in Table I only as an upper limit. The transition labeled γ_2 is expected to go primarily to the $\frac{3}{2}^-$ level rather than to the nearby $\frac{5}{2}^+$ level. In ^{13}N these transitions are unresolved, while in ^{13}C the 170-keV energy separation allows us to put an upper limit of 20% on the $\frac{5}{2}^+$ contribution. The presence of a small $E1$ contribution would not substantially alter our conclusions since $E1$ and $M1$ transition rates have the same energy dependence. Systematic errors in Γ_{γ_1} and Γ_{γ_2} introduced by the tails of the unbound levels in ^{13}N are smaller than our statistical un-

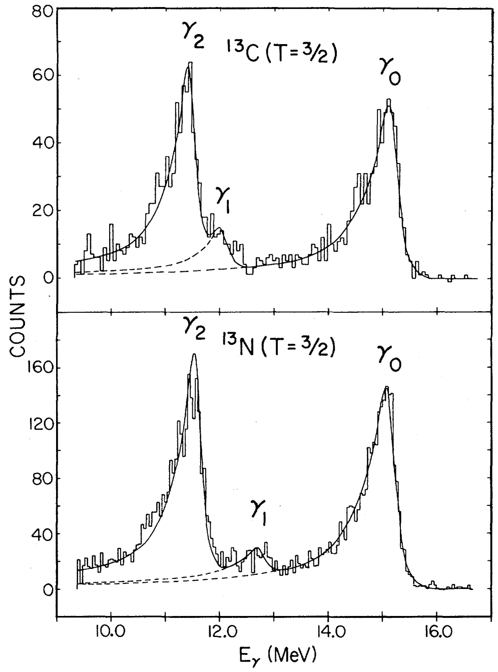

FIG. 2. γ-ray spectra from the decay of the $T=\frac{3}{2}$ levels in ^{13}C and ^{13}N. The smooth curves are least-squares–fitted line shapes.

certainties and have been neglected.

For the purpose of comparing the reduced transition strengths in ^{13}C and ^{13}N it is convenient to define the asymmetry parameter $\delta = B(^{13}\mathrm{C})/B(^{13}\mathrm{N}) - 1$, which is shown in Table I. The precision of our comparison may be extended for the $M1$ transitions by defining the relative asymmetry $\Delta = B_{\gamma_2}(^{13}\mathrm{C})B_{\gamma_0}(^{13}\mathrm{N})/B_{\gamma_0}(^{13}\mathrm{C})B_{\gamma_2}(^{13}\mathrm{N}) - 1$, since Δ is independent of the absolute strengths.

Since the $M1$ operator contains no radial dependence in the long-wavelength limit, and the γ_0 and γ_2 transitions are strong, the asymmetries for these transitions provide a good opportunity to examine the structure of the electromagnetic current itself. Defining A_2 and A_1 as the reduced isotensor and isovector transition amplitudes, respectively, the resulting "isotensor" asymmetries are given by $\delta \doteq 4(\frac{3}{5})^{1/2}A_2/A_1$ and $\Delta = 8(\frac{3}{5})^{1/2}\overline{A}$, where $\overline{A} \equiv \frac{1}{2}[A_2/A_1(\gamma_2) - A_2/A_1(\gamma_0)]$. Upper limits for A_2/A_1 and $\overline{A}$ are given in Table I.

Table I also displays the asymmetries expected from a shell-model calculation of Coulomb and electromagnetic spin-orbit effects,[15] and from a hypothetical isotensor electromagnetic current.[14] The asymmetries expected from both sources are smaller than our experimental upper limits. Thus, even though the experimental results have placed a good upper limit on the reduced isotensor matrix element A_2, the corresponding limit for the isotensor current is not very stringent since, even if the $\Delta T = 2$ current exists, its effects in nuclei are highly suppressed.

In contrast to the $M1$ transitions, surprisingly large asymmetries are seen in the $E1$ transitions

TABLE I. γ-transition strengths in ^{13}C and ^{13}N. Reduced transition strengths are in Weisskopf units.

	$E_i(J^\pi,T)$	$E_f(J^\pi,T)$	Γ_γ(eV)	B(W.u.)	δ(exp.)	δ(theory)	$\lvert A_2/A_1\rvert$
^{13}C ^{13}N	15.11 15.07 (3/2⁻,3/2)	0.0 0.0 (1/2⁻,1/2)	22.7 ± 2.6[a] 24.2 ± 1.5 (M1)	0.318 ± 0.036 0.342 ± 0.021 (M1)	-0.07 ± 0.13	0.01[e] -0.049[f]	< 0.065
^{13}C ^{13}N	15.11 15.07 (3/2⁻,3/2)	0.0 0.0 (1/2⁻,1/2)	0.59 ± 0.11[a] 0.32 ± 0.12 (E2)	0.51 ± 0.10 0.28 ± 0.11 (E2)	$0.82^{+1.2}_{-0.6}$		
^{13}C ^{13}N	15.11 15.07 (3/2⁻,3/2)	3.68 3.51 (3/2⁻,1/2)	18.2 ± 2.4[b] 19.6 ± 1.4[b] (M1)	0.587 ± 0.077 0.613 ± 0.044 (M1)	-0.04 ± 0.14	0.003[e]	< 0.058
^{13}C ^{13}N	15.11 15.07 (3/2⁻,3/2)	3.09 2.37 (1/2⁺,1/2)	4.12 ± 0.74 ≤2.82 ± 0.30 (E1)	$(6.4 \pm 1.1)\times 10^{-3}$ $\leq(3.69 \pm 0.39)\times 10^{-3}$ (E1)	≥0.83 ± 0.29		
^{13}C ^{13}N	3.09 2.37 (1/2⁺,1/2)	0.0 0.0 (1/2⁻,1/2)		0.040 ± 0.005[c] 0.13 ± 0.01[d] (E1)	-0.69 ± 0.05		
					Δ = 0.03 ± 0.07[g]	-0.007[e]	$\overline{A}$ < 0.016[g]

[a]Ref. 11.

[b]This may contain a small unresolved component (see text).

[c]Ref. 12.

[d]Weighted average from Ref. 13 and references therein.

[e]Isotensor, Ref. 14.

[f]Charge dependent, shell model, Ref. 15.

[g]See text.

from the $T=\frac{3}{2}$ levels in ^{13}C and ^{13}N. There is also some evidence for a large asymmetry in the $E2$ component of the ground-state transitions. That these asymmetries are probably not due to a $\Delta T=2$ electromagnetic current can be seen by examining the mirror $E1$ decays involving the ground and first two excited states in mass 13. Since the $E1$ operator is a pure isovector in the long-wavelength limit, corresponding $T=\frac{1}{2}\rightarrow T=\frac{1}{2}$ $E1$ transitions in ^{13}C and ^{13}N should have the same strength if the isospin symmetry were exact. In this case a $\Delta T=2$ current cannot produce an asymmetry because it does not connect $T=\frac{1}{2}$ levels. Effects due to isospin *mixing* should be negligible for the $T=\frac{1}{2}$ decays. Using the known isospin-forbidden particle decay widths,[6] we estimate that effects of isospin mixing on the $T=\frac{3}{2}$ γ decays are also negligible. Since large asymmetries are observed in $T=\frac{1}{2}\rightarrow T=\frac{1}{2}$ $E1$ decays in mass 13[12,13] (see Table I), we must conclude that a substantial breakdown of mirror symmetry has occurred. We believe that the asymmetries in the $T=\frac{3}{2}\rightarrow T=\frac{1}{2}$ $E1$ (and $E2$) transitions are likewise due to a violation of strict mirror symmetry.

Charge asymmetries are also observed in mirror Gamow-Teller β decays[16] and mirror pickup reactions.[17] These asymmetries are attributed to differences in the radial wave functions caused by differences in the binding energies. To determine whether such binding-energy effects can explain the $E1$ asymmetries in mass 13 we have examined the $E1$ decays of the lowest J^π, $T=\frac{1}{2}^+, \frac{1}{2}$ levels in ^{13}C and ^{13}N. One would expect that binding-energy effects would be especially pronounced in this case since they produce a Thomas-Ehrman shift in the $\frac{1}{2}^+$ levels of ~0.7 MeV. These transitions are unusally strong, so that small changes in interfering components of the transition matrix elements should not produce large asymmetries.

The binding energy for the $E1$ widths was calculated by use of a simple one-body model following the ideas used to investigate the β asymmetry in mass 12.[18] Separate charge-independent Woods-Saxon wells (plus a Coulomb potential) were used to generate radial wave functions for the ground and first excited states in ^{13}C and ^{13}N with the correct binding energies. Using the same spectroscopic factors[13] for ^{13}C and ^{13}N, we calculate $B(^{13}\mathrm{C})=B(^{13}\mathrm{N})=0.16$ Weiskopf units. Thus simple binding-energy effects of this kind do not explain the large charge asymmetry in the $E1$ transitions. Apparently the data require a significant degree of charge-dependent configuration mixing. The origin of this unexpectedly large degree of mixing is an important and unresolved issue.

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