Gamow-Teller sum rules and the $^{14}C(^6Li,^6He)^{14}N$ reaction

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A correlation between the (^{6}Li,^{6}He) cross sections and the Gamow-Teller strength observed previously for other targets persists in the $^{14}C(^6Li,^6He)^{14}N$ reaction. The total Gamow-Teller strength up to 12 MeV excitation is measured and we derive sum rules for the Gamow-Teller strength which depend on the *LS* configurations of the target state. The extracted *LS* configuration of the ^{14}C ground state is in serious disagreement with shell model calculations. There are several inconsistencies within our understanding of the nuclear structure and transition strengths in these nuclei, part of which is attributable to mesonic currents. Constraints are also placed upon the (^{6}Li,^{6}He) reaction mechanism.

[NUCLEAR REACTIONS $^{14}C(^6Li, ^6He)^{14}N$, $E = 62$ MeV; measured $\sigma(\theta)$. Deduced GT sum rule and ^{14}C ground state wave function.]

INTRODUCTION

We have measured angular distributions of the $^{14}C(^6Li, ^6He)^{14}N$ reaction at 62 MeV bombarding energy. In an earlier Letter[1] we presented some of these data showing an excellent correlation between the known Gamow-Teller (GT) strength and the $L = 0$ component of the (^{6}Li, ^{6}He) cross sections. At the present time, we amplify this work and derive Gamow-Teller sum rules which we apply to our data to obtain information about the ^{14}C ground state.

Recently, an excellent correlation between the 0° (p,n) cross sections[2] and the Gamow-Teller matrix element between the initial and final nuclear states has been observed at $T = 120$ MeV. Although the (p,n) reaction, unlike the (^{6}Li, ^{6}He) reaction, has the problem of separating the Gamow-Teller (spin-flip) transitions from Fermi (non-spin-flip) transitions, the effective nucleon-nucleon interaction at 120 MeV enhances the spin-flip transitions by a factor[2] of 4.5. With the imminent possibility of mapping out the Gamow-Teller strength distributions, it is timely to examine the relationship between Gamow-Teller sum rules and the target ground state properties.

I. THE DATA

The experiment was performed on the Oak Ridge Isochronous Cyclotron (ORIC). A 3-wire Kopp-Borkowski position sensitive proportional counter in the focal plane of the ORIC broad range spectrograph was used to identify the ^{6}He particles and determine their energy from a two-dimensional ΔE vs position array. The counter was run at 1 atmosphere with a 0.025-mm thick Mylar window. An additional 0.125 to 0.150 mm of aluminum was placed in front of the detector to reduce background. Further details of the experiment are given in our previous report.[1] Two energy spectra at $\theta = 2°$ and 4° are shown in Fig. 1. At 2° the intensity of the singly charged ^{6}Li is sufficient to cause noticeable background due to inadequate ΔE resolution. This background was estimated by placing a larger mask than the ^{6}He mask in the ΔE vs position display and subtracting the additional counts in the spectrum from the original ^{6}He spectrum. The spectra show the dominance of the 3.95 MeV 1^+ state. At 2° this state is populated over a factor of 10 more than any other state except for the 5.11 MeV 2^- and the 8.49 MeV 4^-. The angular distributions in Figs. 2 and 3 show that the 3.95 MeV state is the only one with an $L = 0$ shape (see also Ref. 1). The only other angular distribution with a rising cross section between 4° and 2° is the 5.11 MeV 2^- state. All transitions with $L \geq 2$ are characterized by cross sections decreasing with angle between 4° and 2°. This is evidence of the 3.95 MeV state collecting at least 95% of the $L = 0$ cross section to states below 12 MeV excitation. Because of the excellent correlation between the $L = 0$ cross section and the Gamow-Teller strength,[1,3] we conclude that the 3.95 MeV state has at least 90% of the GT strength below 12 MeV excitation. The 1^+ ground state has no noticeable $L = 0$ component in its cross section and its angular distribution has an identical shape (within statistical errors) as the 2^+ state at 7.03 MeV excitation indicating $L = 2$. The lack of $L = 0$ cross section to the ground state is in agreement

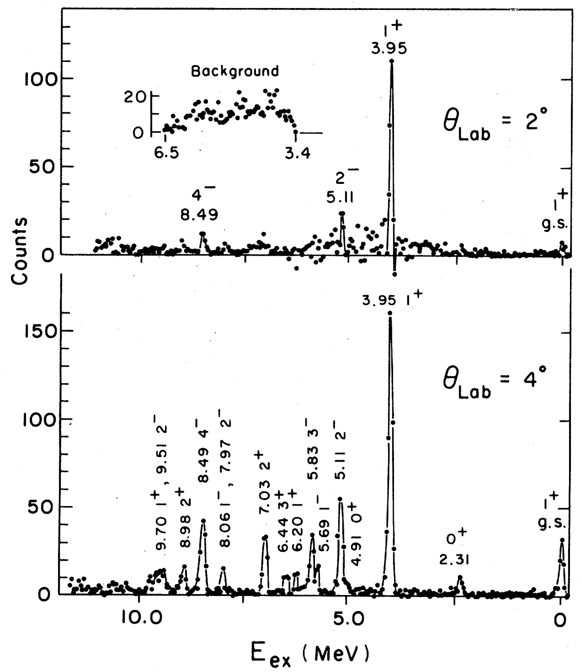

FIG. 1. Spectra of the $^{14}C(^6Li, ^6He)^{14}N$ reaction at $E_{Lab} = 62$ MeV. Also shown is a background of misidentified ^6Li which is subtracted from the 2^0 ^6He spectrum.

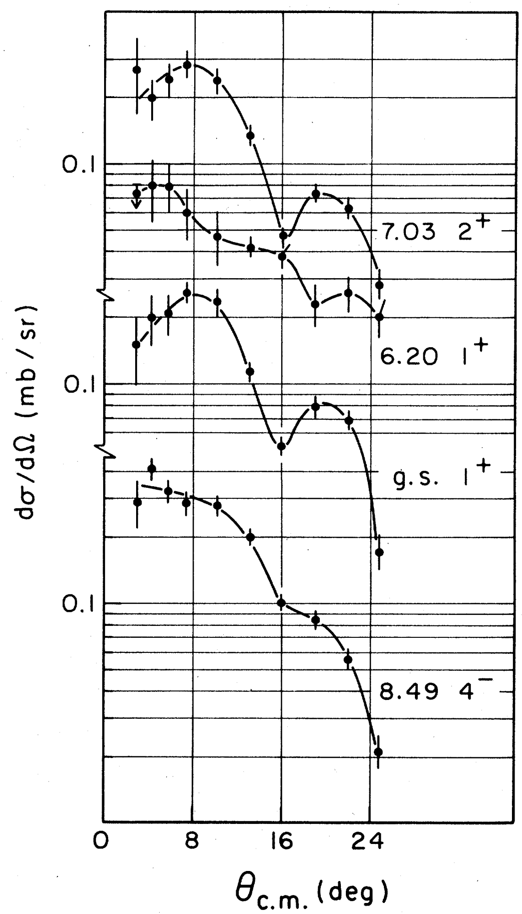

FIG. 2. Center of mass differential cross sections for the $^{14}C(^6Li, ^6He)^{14}N$ reaction at 62 MeV.

with the very large *ft* of the GT β decay to this state.

This is surprisingly good agreement, because both the (p, n) reaction at proton energies below 20 MeV (Ref. 4) and also the $(^3He, t)$ reaction[5] show the 1^+ ground state to have angular distributions which deviate significantly from a pure $L = 2$ shape. This goes counter to the expectation that the $(^6Li, ^6He)$ reaction has the more complicated reaction mechanism; is not governed by simple GT and $L = 2$ matrix elements; and thereby is not expected to have a simple $L = 2$ angular distribution to the ground state. This mystery as to why the $(^6Li, ^6He)$ reaction reflects the simple matrix elements better than the (p, n) and $(^3He, t)$ reaction is still unexplained. Even more puzzling, we have direct evidence that multistep processes are important in the $^{14}C(^6Li, ^6He)^{14}N$ reaction. The cross section to the 0^+, $T = 1$ 2.31 MeV state is about $\frac{1}{3}$ the cross section to the ground state, but must be entirely due to a nonlocal interaction[3,6] as in multistep processes. This follows from the necessity of an $L = 1$ transfer to 0^+ states, which conserves total angular momentum but violates the parity rule of a local interaction:

$$\pi_{\text{initial}}\,\pi_{\text{final}} = (-1)^L \,.$$

It is no easy task to calculate cross sections of multistep processes in the $(^6Li, ^6He)$ region. A major problem is that there are many possible multistep processes and a theoretical calculation should not arbitrarily select one process over others. Any such calculation needs a lot of data and therefore we present some of our other angular distributions in Figs. 2 and 3.

II. CONSTRAINTS ON THE REACTION MECHANISM

The transition $^{14}C(^6Li, ^6He)^{14}N_{g.s.}$ with its lack of an $L = 0$ cross section puts a great constraint upon the possible multistep reaction mechanisms. The small GT matrix element between the $^{14}C_{g.s.}$ and the $^{14}N_{g.s.}$ results from a delicate cancellation of the individual components of the matrix element and is *not* a result of different nuclear structure of the 0^+ $^{14}C_{g.s.}$ and the 1^+ $^{14}N_{g.s.}$. There is ample experimental data that both states have predominantly the same nuclear-shell model configuration, $(1S)^4(1P)^{10}$ or equivalently a $(1P)^{-2}$ configuration based upon an ^{16}O doubly closed core. The reason for the small GT matrix element is that the 1^+ state at 3.95 MeV is a giant resonance tak-

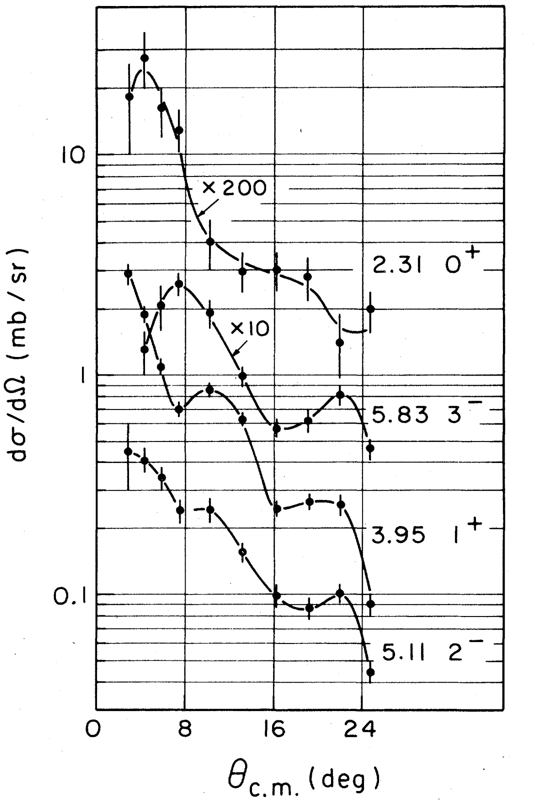

FIG. 3. Center of mass differential cross sections for the $^{14}C(^6Li, ^6He)^{14}N$ reaction at 62 MeV.

ing all of the GT strength. The $^{14}C_{g.s.}$ has the two components $(1P_{3/2})^{-2}$ and $(P_{1/2})^{-2}$. The $^{14}N_{g.s.}$ has three components: $(1P_{3/2})^{-2}$, $1P_{1/2}{}^{-1}\,1P_{3/2}{}^{-1}$, and $(1P_{1/2})^{-2}$. The GT matrix element, $\langle ^{14}C_{g.s.}|\vec{\sigma}\cdot\vec{\tau}| \times {}^{14}N_{g.s.}\rangle$, has four components: $(1P_{3/2})^{-2} \rightarrow (1P_{3/2})^{-2}$, $(1P_{3/2})^{-2} \rightarrow 1P_{1/2}{}^{-1}1P_{3/2}{}^{-1}$, $(1P_{1/2}{}^{-2}) \rightarrow (1P_{1/2}{}^{-2})$, and $(1P_{1/2}{}^{-2}) \rightarrow 1P_{1/2}{}^{-1}1P_{3/2}{}^{-1}$. These four transition amplitudes add coherently and must cancel each other so perfectly that the total GT matrix element is less than 1% of its single largest component,

$$\langle ^{14}C_{g.s.}\|\vec{\sigma}\cdot\vec{\tau}\|\,^{14}N_{g.s.}\rangle = \pm\, 0.0084\,.$$

In order to appreciate the smallness of this number, we give another matrix element between the same two states which we estimate from the measured[7] $\gamma(M1)$ decay of the isobaric analog of ^{14}C at 2.31 MeV excitation in ^{14}N,

$$\langle ^{14}C_{g.s.}\|\vec{1}\cdot\vec{\tau}\|\,^{14}N_{g.s.}\rangle = \pm\, 1.7\,.$$

The $^{14}C(^6Li, ^6He)^{14}N$ reaction, whether quasielastic or multistep, will have the four similar transition amplitudes as mentioned above for the β decay. In addition, if the reaction is multistep, there may be two additional transition amplitudes: $(1P_{3/2})^{-2} \rightarrow (1P_{1/2})^{-2}$ and $(1P_{1/2})^{-2} \rightarrow (1P_{3/2})^{-2}$.

We have placed an experimental upper limit of 0.3% on the $L=0$ cross section of the ^{14}N ground state as compared to the ^{14}N 3.95 MeV state, and estimate that these six transition amplitudes must be canceling each other to below the 20% level. In other words, the total amplitude for the reaction is less than 20% of the single largest component in the amplitude. This upper limit is far from the very accurate precision in the β-decay measurement which places the cancellation at the 1% level, but nevertheless serves as a useful constraint upon models for the reaction mechanism.

A good way to see this constraint is by illustration. Consider that the reaction is proceeding by the two step process $^6Li \rightarrow {}^7Li \rightarrow {}^6He$ via intermediate states in ^{13}C and ^7Li. We can describe the intermediate states in ^{13}C as a ^{14}C ground state core coupled to a neutron hole: either $(1P_{3/2})^{-1}$ or $(P_{1/2})^{-1}$. Both types of intermediate states, $[^{14}C \times (1P_{3/2})^{-1}]$ or $[^{14}C \times (1P_{1/2})^{-1}]$, must contribute in an equal way to the reaction. Otherwise the transition amplitudes, $(1P_{3/2})^{-2} \rightarrow (1P_{j1})^{-1}(1P_{j2})^{-1}$, will be out of balance with the transition amplitudes $(P_{1/2})^{-2} \rightarrow (1P_{j1})^{-1}(1P_{j2})^{-1}$ ($j1, j2 = \frac{1}{2}$ or $\frac{3}{2}$) and the cancellation will not reach the 20% level. Two things that destroy the balance between the transition amplitudes are differences in the energy and spectroscopic strength of the intermediate states. The $\frac{3}{2}^-$ ^{13}C ground state takes much of the $[^{14}C \times (1P_{3/2})^{-1}]$ strength and the $\frac{1}{2}^-$ level at 3.68 MeV excitation in ^{13}C takes much of the $[^{14}C \times (1P_{1/2})^{-1}]$ strength.[7] If the balance between the transition amplitudes is to be preserved then there must be a sufficiently weak dependence of the reaction amplitude upon variations of 3.7 MeV in the energy of the intermediate states, and each state must exhaust the same percentage of the spectroscopic strength ($P_{3/2}{}^{-1}$ and $P_{1/2}{}^{-1}$) respectively. Extensive multistep calculations are needed to understand the remarkable preservation of the GT matrix element in the $(^6Li, ^6He)$ reaction.

III. GAMOW-TELLER SUM RULES

Until the discovery that the $(^6Li, ^6He)$ reaction can be used to map out the Gamow-Teller strength, it was not possible to measure the total Gamow-Teller strength between nuclei. The β decay is limited by energy conservation to decay to nuclear states with lower energy than the parent (minus 511 keV). The Gamow-Teller strength to the 1^+ states at 6.20, 9.70, 11.07, 11.36, and 13.71 MeV and higher excitation energies could not be measured by β decay. Since it is possible to make such measurements using the $(^6Li, ^6He)$ reaction, it is useful to derive sum rules which relate the total Gamow-Teller strength to the properties of the target or parent nucleus. The derivation of the sum rule requires calculating the reduced matrix element, RME, in the equation for the summed Gamow-Teller strength:

$$\mathrm{SUM(GT)} = \frac{1}{2(2J_a+1)} \sum_b \frac{1}{(2T_b+1)} [\langle T_a T_{z,a} 1 \pm 1 | T_b T_{z,b} \rangle \times \langle b \| \sigma\tau \| a \rangle]^2 .$$

The RME can be very complicated if we allow the target state to have a wide variety of configurations, and it is not practical to derive a general sum rule which is valid for all targets. Therefore we will restrict our attention to ^{14}C. We will describe ^{14}C as having an inert core of six protons and six neutrons which do not contribute to the reaction. We will assume this inert core has seniority zero, zero total angular momentum, and zero total isospin. No restriction will be placed upon the remaining two valence nucleons. These two valence neutrons will be described as each having orbital angular momentum l and coupled to total spin S, total angular momentum L, and total isospin $T=1$. We will sum over all possible configurations, l^2SLT. Here we are using LS coupling because of its natural simplicity for the Gamow-Teller matrix element,

$$\mathrm{RME} = \sum_{l,S,L,S',L'} \left\langle l^2 S' L' J_b T_b \left\| \sum_{i=1,2} \vec{\sigma}(i)\vec{\tau}(i) \right\| l^2 S L J_a T_a \right\rangle \times A_{lSLT} B_{l'S'L'T'} ,$$

where A_{lSLT} is the amplitude of the l^2SLT configuration in the ^{14}C target and $B_{l'S'L'T'}$ is the amplitude of the $l^2S'L'T'$ configuration in the residual nucleus. Solving for the RME explicitly we obtain

$$\mathrm{RME} = \sum_{LSLS'L'} A_{lSL} B_{lS'L'} n \langle \tfrac{1}{2} l \| \sigma \| \tfrac{1}{2} l \rangle \langle \tfrac{1}{2} \| \tau \| \tfrac{1}{2} \rangle$$
$$\times \sum_{S_1 L_1 T_1} [l^2 S L T_a \{ | l(S_1 L_1 T_1) l S L T_a] [l(S_1 L_1 T_1) l S' L' T_b | \} l^2 S' L' T_b]$$
$$\times (-1)^{S_1+S+L_1+l+L+T_1T_a+1} [(2J_a+1)(2J_b+1)3(2T_a+1)(2T_b+1)(2S+1)(2S'+1)(2L+1)(2L'+1)]^{1/2}$$
$$\times \begin{Bmatrix} S & L & J_a \\ S' & L' & J_b \\ 1 & 0 & 1 \end{Bmatrix} \begin{Bmatrix} \tfrac{1}{2} & S & S_1 \\ S' & \tfrac{1}{2} & 1 \end{Bmatrix} \begin{Bmatrix} l & L & L_1 \\ L' & l & 0 \end{Bmatrix} \begin{Bmatrix} \tfrac{1}{2} & T_a & T_1 \\ T_b & \tfrac{1}{2} & 1 \end{Bmatrix} .$$

Also, because of our restriction on the core of 12 inactive nucleons, S_1, L_1, and T_1 must have the values of one of the single valence nucleons, $S_1 = \frac{1}{2}$, $L_1 = l$, and $T_1 = \frac{1}{2}$. Substituting in these values we obtain

$$\mathrm{RME} = \sum_l (-6A_{l00}B_{l00} + 2\sqrt{3}A_{l11}B_{l01}) \quad \text{for } T_b = 0,$$

$$\mathrm{RME} = \sum_l (4\sqrt{3}A_{l11}B_{l11}) \quad \text{for } T_b = 1 .$$

It is understood that the amplitudes $B_{lS'L'}$ are for a particular final state, b. And by completeness, the sum over all final states gives

$$\sum_b [B_{lS'L'}(b)]^2 = 1 .$$

Combining equations, we obtain

$$\mathrm{SUM(GT)} = \sum_l (6A_{l00}^2 + 6A_{l11}^2) = 6 .$$

Here the sum over l is implicitly understood to include a sum over the principal quantum number. For example, the amplitude for the valence neutrons being in the $2P$ shell is included in the sum as well as the amplitude for the $1P$ shell. We see by this result that the sum of the GT strength is independent of the ^{14}C wave function. Specifically it is independent of the single-particle shells occupied by the valence nucleons (i.e., $1P$, $2s$, $1d$, etc.). Furthermore, it is independent of whether the two valence nucleons are coupled to a $^1S_0$ or $^3P_0$ LS configuration. If instead of summing over all final states we sum over states of a particular isospin, $T_b = 0$ or 1, we obtain the partial sum rules, respectively:

$$\mathrm{SUM}_{T0}(\mathrm{GT}) = \sum_l (6A_{l00}^2 + 2A_{l11}^2) ,$$

$$\mathrm{SUM}_{T1}(\mathrm{GT}) = \sum_l 4A_{l11}^2 .$$

These sum rules depend strongly upon the amount of $^1S_0$ and $^3P_0$ configurations in the ^{14}C ground state but are still independent of the single-particle shell in which the valence nucleons reside. By measuring either partial sum rule, it is possible to uniquely determine the amount of the $^1S_0$

and $^3P_0$ configurations in the ^{14}C ground state.

The only assumption that has gone into the derivation of these sum rules is the inertness of the 12 nucleon core. By this assumption the single-particle operator $\vec{\sigma}, \vec{\tau}$, operating upon a single nucleon in the core, must give zero according to the Pauli principle because the corresponding proton state is assumed to be already occupied. Secondly, the core must have zero total spin and zero total isospin such that the two valence nucleons couple together to give the total spin and isospin of the nucleus. The assumption could be tested by measuring the total sum rule and its deviation from the expected value of 6.

IV. THEORY VS EXPERIMENT

The results of the $^{14}C(^6Li, ^6He)^{14}N$ reaction indicate that at least 90% of the GT strength below 12 MeV excitation is in the 3.95 MeV state. This is in agreement with the shell model calculations. We refer to the calculation of Visscher and Ferrell[8] which places 97% of $SUM_{T0}(GT)$ in the 3.95 MeV state and the calculation of Cohen and Kurath[9] which also places 97% of $SUM_{T0}(GT)$ in the 3.95 MeV state. Whereas the percentages agree with each other, the absolute GT strength to the 3.95 MeV state, $B(GT)_2$, for two theories and the experimental measurement are at variance with each other. VF gives $B(GT)_2 = 4.2$, CK gives $B(GT)_2 = 4.81$, and experiment gives $B(GT)_2 = 2.39 \pm 0.45$. Basically this means that the $SUM_{T0}(GT)$ for the three are also at variance with each other. The theoretical calculations and the experimental results are summarized in Table I. The experimental $B(GT)_2$ is obtained from the measured $^{14}O(\beta^+)$ $^{14}N(3.95)$ decay, where the $^{14}O_{g.s.}$ is assumed to be an isobaric analog of the $^{14}C_{g.s.}$. Kavanaugh has published two values[10] for the branching ratio of the β^+ decay to the 3.95 MeV state: $(3.5 \pm 1.0) \times 10^{-4}$ and $(6.2 \pm 0.7) \times 10^{-4}$. No explanation of the discrepancy between the two numbers has been presented and therefore Deahnick[11] recently remeasured the branching ratio obtaining the value $(4.5 \pm 0.8) \times 10^{-4}$. Using this later value, we obtain $ft = 1730 \pm 320$ which is related to $B(GT)$ by the equation

$$B(GT) = 6250/1.51\, ft\,.$$

Let us assume that $B(GT)_2$ represents 97% of $SUM_{T0}(GT)$ and use the sum rule to obtain the $^1S_0$ and $^3P_0$ components of the ^{14}C ground state. These results are listed under SUM_{T0} in Table II along with theoretical calculations. Table II shows that the discrepancies in the value of $SUM_{T0}(GT)$ represent huge variations in the LS composition of the ^{14}C ground state. A quick comparison of the $SUM_{T0}(GT)$ result with the VF and CK wave functions suggests that our experiment is missing some of the $T=0$ GT strength and therefore is underestimating the amount of $^1S_0$ in the ^{14}C ground state. This suggestion assumes that the CK matrix elements, which have experienced great success, could not be so much in error. However, this may not be the correct assumption. Firstly, the CK calculations put 97% of the $T=0$ GT strength in the 3.95 MeV state in agreement with the assumption used in calculating $SUM_{T0}(GT)$. Secondly, the CK and also the VF calculations are restricted solely to the $1P$ shell which makes them in error. In contrast, the sum rule is much more general, allowing the two valence nucleons to be in any shell.

If the experimental lower limit, 90% of the $SUM_{T0}(GT)$, is used for the 3.95 MeV state, the sum rule gives 16% $^1S_0$ for the ^{14}C ground state. This is still in serious disagreement with CK. A reasonable way to alter the CK wave functions to agree with experiment is to allow (s,d) shell components in all the wave functions. The disagreement can then be resolved by having (s,d) strength in the $^{14}N(3.95)$ transition interfering destructively with the $1p$ strength reducing the total strength by

TABLE I. Wave functions in jj coupling ($A_{2j_1,2j_2}$) and Gamow-Teller transition strengths.

	VF	CK	This experiment
$A_{11}(0^+)$	0.969	0.914	
$A_{33}(0^+)$	0.251	0.405	
$A_{11}(1_1^+)$	0.925	−0.975	
$A_{13}(1_1^+)$	0.120	−0.208	
$A_{33}(1_1^+)$	0.361	0.076	
$A_{11}(1_2^+)$	−0.367	−0.174	
$A_{13}(1_2^+)$	0.931	0.932	
$A_{33}(1_2^+)$	0.04	0.318	
$B(GT)_1$	0	0.142	<2%
$B(GT)_2$	4.2	4.81	>90%
$B(GT)_{T=0\ \text{remain}}$	0.141	2×10^{-4}	<8%

TABLE II. The LS composition of ^{14}C ground state.

	$^1S_0$	$^3P_0$
SUM_{T0}	12 ± 11%	88 ± 11%
VF	58.5%	45.5%
CK	74%	26%

a factor of 2. This possibility is inconsistent with our description of the 3.95 MeV state as the Gamow-Teller giant resonance. It would imply that there is a 1^+ state(*s*) at higher excitation energy with constructive interference between its $1p$ and (s,d) configurations. No such state is seen in our experiment below 12 MeV excitation.

Interestingly, the GT sum rule result is in excellent agreement with Ensslin *et al.*,[12] who also find that the ^{14}C ground state is nearly a pure spin triplet state. Ensslin *et al.*[12] restrict their shell model space to two holes in the $1p$ shell and assume the 2.313 MeV ^{14}N 0^+ state is a perfect isobaric analog of the ^{14}C ground state. With these assumptions they find a unique set of wave functions for the ^{14}C and ^{14}N ground states which give the experimentally measured $^{14}C(\beta^-) \rightarrow {}^{14}N$ ground state *ft* value, the ^{14}N g.s. magnetic moment, the ^{14}N g.s. quadrupole moment, and the electron inelastic form factor for excitation of the 2.313 MeV ^{14}N 0^+ state. Considering that the $^{14}C(\beta^-)$ ^{14}N g.s. GT matrix element is nearly zero, we note that all of these experimental data are essentially independent of the GT sum rule and, yet, they remarkably give the same ^{14}C g.s. wave function as does the GT sum rule.

If Ensslin *et al.* wave functions are correct, it is a real surprise, because they are in complete disagreement with CK wave functions which use the same shell model space. In spite of their apparent success in reproducing some of the data, it is likely that these wave functions are in error. We get a clue of this by examining the 3.95 MeV ^{14}N 1^+ state. If the ^{14}C and ^{14}N ground states are nearly pure triplet states the 3.95 MeV state must be an almost pure singlet state. In fact by imposing orthogonality with the Ensslin ^{14}N (1^+) g.s. and using the measured $^{14}O(\beta^+)$ $^{14}N(3.95)$ *ft* value we can obtain a unique solution for the $^{14}N(3.95)$ state in the restricted $(1p)^{-2}$ model space. This solution severely underestimates, by more than a factor of 10, both the $M1$ and $E2$ transitions strengths[7] for $^{14}N(3.95) \rightarrow {}^{14}N$(g.s.).

A more basic discrepancy appears between two experimental measurements. The $M1$ decay between the 3.95 MeV state and the $^{14}N(2.31)$ 0^+ state has a width $\Gamma(M1) = 0.140 \pm 0.013$ eV.[13] Because $^{14}N(2.31)$ is the isobaric analog of the $^{14}O_{g.s.}$, the $M1$ decay involves the same GT matrix element as the $^{14}O(\beta^+)$ $^{14}N(3.95)$ transition. Although this isovector $M1$ transition is dominated by the spin contribution, it also has a small current contribution which can be estimated from CK and VF wave functions to be $\langle 3.95 \| l\tau \| 2.31 \rangle = -2.75 \pm 0.75$. The extracted spin contribution gives $B(\mathrm{GT})_2 = 4.15 \pm 0.4$, which is in serious disagreement with the $^{14}O(\beta^+)$ decay.[11] No reasonable alteration in $\langle 3.95 \| l\tau \| 2.31 \rangle$ including the use of Ensslin wave functions can resolve this discrepancy.

This apparent discrepancy between the experimentally known $M1$ moment and *ft* value is not new. Yoro[13] found similar discrepancies when examining $M1$ moments and β-decay *ft* values between mirror nuclei in the $1p$ shell. He attributed the problem to the quenching of the axial vector coupling constant in β decay by mesonic degrees of freedom in nuclear matter.[14] This quenching apparently is not affecting $M1$ moments by the same amount. There is also a quenching due to configuration mixing, core polarization, etc. which should affect the β decay and $M1$ moments equally. These two quenching effects are not independent of each other. Allowing the effective coupling constants in β decay to be a free parameter to fit the data, Yoro[13] found it to be normalized downward by 20% from its free space value. This renormalization has the effect of increasing $B(\mathrm{GT})$ extracted from β decay by about 45% and would help resolve the discrepancies which we observe.

Recently Petrovich *et al.*[15] have studied $M1$ excitations using the (p,n) reaction. Using form factors from inelastic electron scattering they concluded that the isovector spin-flip components of the GT matrix interaction should be normalized downward by 1.4 from earlier values.[16] It would be interesting to study whether this renormalization is masking an effect similar to what Yoro saw between β-decay *ft* values and the $M1$ moments.

V. FUTURE DIRECTION

We have shown that the partial GT sum rules, $\mathrm{SUM}_{T0}(\mathrm{GT})$ and $\mathrm{SUM}_{T1}(\mathrm{GT})$, are very sensitive to the LS composition of the ^{14}C wave function ($^1S_0$ and $^3P_0$). There is a large variation in the experimental and theoretical values of $\mathrm{SUM}_{T0}(\mathrm{GT})$ which is reflected in greatly different percentages of the $^1S_0$ and $^3P_0$ components of ^{14}C. Similar variations in $M1$ matrix elements observed earlier by Yoro have been attributed to mesonic exchange currents which affect beta decays differently from the isovector magnetic moments. The sum rules have a simple relationship to the ^{14}C ground state and should be a powerful tool in studying the effects of mesonic currents. There are several ways of pursuing these studies. Firstly, the $^{14}O(\beta^+)$ $^{14}N(3.95)$ branching ratio should be improved to 10% accuracy. Secondly, either or both the $^{14}C(^6Li, ^6He)^{14}N$ and $^{14}C(p,n)$ ^{14}N reactions should be redone to measure the GT strength to the 1^+ $T=1$ level at 13.71 MeV in ^{14}N. Theories predict this state to have essentially all of the $\mathrm{SUM}_{T1}(\mathrm{GT})$. By measuring $\mathrm{SUM}_{T1}(\mathrm{GT})$ we will obtain $\mathrm{SUM}(\mathrm{GT})$. Any deviation of $\mathrm{SUM}(\mathrm{GT})$ from 6 is very likely due to mesonic current and core polarization effects. For many years $^{14}C_{g.s.}$ and $^{14}N_{g.s.}$ have been two of the most carefully studied nuclear states and the small GT matrix element between them has been very informative. There are apparently several inconsistencies within our understanding of the nuclear structure and transition strengths. To extend this study to total GT sum rules should add to our general understanding of this problem.

Note added in proof. Figureau *et al.*[17] have published an analysis of the $^{14}N(\gamma,\pi)^{14}C_{g.s.}$ transaction showing a discrepancy between the theoretical and experimental cross section. They also found that the Ensslin *et al.*[12] wave functions led to better agreement between theory and experiment, and suggested that these wave functions account for meson exchange and other corrections.

One of us, W. R. Wharton, did the initial stages of this experiment while at Rutgers University.

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