Relationship between Gamow-Teller Transition Probabilities and (*p,n*) Cross Sections at Small Momentum Transfers

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Gamow-Teller transition probabilities are extracted for eight nuclei with masses between $A=13$ and 39 from medium-energy (p,n) reactions via the distorted-wave impulse approximation, and compared with experimental β-decay and with free-nucleon transition probabilities. These comparisons indicate strongly that the renormalization of the Gamow-Teller operator needed for (p,n) reactions on finite nuclei is different from that needed for β decay.

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It has become apparent that there is a very close relationship between the Gamow-Teller (GT) reduced transition probabilities $B(\mathrm{GT},\beta)$ obtained from β decay and the cross sections for (p,n) reactions with medium-energy (100–200 MeV) protons at small momentum transfers. In weak-interaction theory the free-nucleon operator for GT β decay is particularly simple, just $\mathbf{s}\tau_{\pm}$, while the operator for the (p,n) reaction may be much more complicated, and may even include two-step contributions. [Matrix elements calculated with the free-nucleon operator will be denoted by B(GT,free).] Usually it is assumed that (p,n) cross sections are proportional to $B(\mathrm{GT},\beta)$ and some kinematic factors. This assumption is based on two observations: (1) When the (p,n) cross section is calculated with a microscopic distorted-wave impulse-approximation (DWIA) code with a realistic effective interaction such as that of Franey and Love,[1] the calculated ratio $B(\mathrm{GT,free})/\sigma(\mathrm{DWIA})$ is nearly constant with respect to variations in the shell-model transition densities. (2) When the experimental (p,n) results can be obtained for transitions with known experimental $B(\mathrm{GT},\beta)$ values, the ratio $\sigma(\mathrm{expt})/\sigma(\mathrm{DWIA})$ is proportional to (and with the Franey-Love or similar interaction nearly equal to) $B(\mathrm{GT},\beta)/B(\mathrm{GT,free})$ over a wide range of mass.[2] These results occur because the $v_{\sigma\tau}$ part of the effective interaction is dominant at these energies, and the $\Delta L=0$ part of the interaction dominates and peaks at small momentum transfer.

In this paper we present evidence that these two ratios are in fact not generally proportional to each other; in addition, we suggest a simple modification of the operator for the (p,n) reaction which accounts quantitatively for the nonproportionality of these ratios as well as for the absolute (p,n) cross sections. We interpret this as a necessary renormalization of the effective (p,n) interaction for finite nuclei in the same sense that the GT β-decay operator must be renormalized.[3,4] This is in sharp contrast to the work of Goodman *et al.*,[5] who interpreted data for $A=13$ and 15 in terms of additional quenching of GT strength (beyond the typical 30% to 40% missing strength) and a "breakdown" of the shell model.

We measured differential cross sections at 135 MeV for targets of mass 14, 15, 17,[6] 18,[7] 26,[8] and 39 which we include in this study. Typical experimental details are given in Ref. 7. Our techniques for reliably determining neutron detection efficiencies (and therefore absolute cross sections) are documented thoroughly[9–12]; thus comparisons with DWIA cross sections can be made in an absolute fashion. Also we include data[5,13] for mass 13 and 19 at 160 MeV based on a lithium-activation technique for determining neutron detection efficiencies. The activation cross sections on which this technique are based were remeasured[12] recently; absolute cross sections based on these new activation data should also be reliable.

In Table I, experimental B(GT) strengths deduced from GT β decays are compared with those deduced from (p,n) cross sections. The β-decay value is obtained from the relation[4]

$$B(\mathrm{GT},\beta)=(g_A/g_V)^{-2}[(6170/ft)-B(\mathrm{F})], \quad (1)$$

TABLE I. Comparison of experimental and theoretical matrix elements for Gamow-Teller–type transitions.

				$B(\mathrm{GT})/3(N-Z)$				
				Experiment		Theory		
A_i	J_i	J_f	E_f (MeV)	β decay[a]	(p,n) cross section	Free nucleon	β eff.	(p,n) eff.
^{13}C	$\frac{1}{2}^-$	$\frac{1}{2}^-$	0.0	0.068	0.13[b]	0.11	0.09	0.14
	$\frac{1}{2}^-$	$\frac{3}{2}^-$	3.51	c	0.46[b]	0.79	0.53	0.50
^{14}C	0^+	1^+	3.95	0.53[d]	0.47[e]	0.80	0.55	0.54
	0^+	1^+	13.7	c	0.15[e]	0.18	0.12	0.11
^{15}N	$\frac{1}{2}^-$	$\frac{1}{2}^-$	0.0	0.086	0.18[e]	0.11	0.09	0.15
	$\frac{1}{2}^-$	$\frac{3}{2}^-$	6.18	c	0.73[e,f]	0.89	0.59	0.55
^{17}O	$\frac{5}{2}^+$	$\frac{5}{2}^+$	0.0	0.36	0.33[g]	0.47	0.31	0.34
	$\frac{5}{2}^+$	$\frac{3}{2}^+$	4.84	c	0.23[g,h]	0.53	0.33	0.33
^{18}O	0^+	1^+	0.0	0.53	0.59[i]	0.84	0.53	0.45
^{19}F	$\frac{1}{2}^+$	$\frac{1}{2}^+$	0.0	0.55	0.71[j]	0.94	0.53	0.53
^{26}Mg	0^+	1^+	1.06	0.19	0.19[k]	0.32	0.20	0.23
^{39}K	$\frac{3}{2}^+$	$\frac{3}{2}^+$	0.0	0.09	0.13[e]	0.20	0.11	0.16
	$\frac{3}{2}^+$	$\frac{5}{2}^+$	1	c	0.36[e]	0.80	0.49	0.36

[a]Unless otherwise noted, these were deduced from the β decay of the state $J_f(E_f)$ as given in the standard compilations and in Brown and Wildenthal (Ref. 14).
[b]Deduced from cross sections given in Ref. 5.
[c]Energetically not allowed in β decay.
[d]Deduced from the ^{14}O to ^{14}N β decay.
[e]From the present experiment.
[f]Includes the strength from $\frac{3}{2}^-$ states at 9.61, 10.5, and 12.5 MeV.
[g]Deduced from cross sections given in Ref. 6.
[h]Includes strength from $\frac{3}{2}^+$ states at 7.3 and 7.6 MeV.
[i]Deduced from cross sections given in Ref. 7.
[j]Deduced from cross sections given in Ref. 13.
[k]Deduced from cross sections given in Ref. 8.
[l]Includes strength from ten $\frac{5}{2}^+$ states between 5.10 and 9.10 MeV.

where $B(\mathrm{F})$ is the Fermi beta-decay contribution. The (p,n) value is defined by

$$B(\mathrm{GT},pn) = B(\mathrm{GT,free})\frac{\sigma(\mathrm{expt}) - \sigma_{\mathrm{F}}(\mathrm{DWIA})}{\sigma(\mathrm{DWIA}) - \sigma_{\mathrm{F}}(\mathrm{DWIA})}, \qquad (2)$$

where the cross sections are taken at small angles. The DWIA cross sections were calculated with DWBA-70[15] with use of the Franey-Love[1] interaction and our microscopic transition densities. Optical-potential parameters were taken from the work of Comfort and Karp[16] (for mass 13), Kelly[17] (for masses 14, 15, 17, 18, and 19), Olmer *et al.*[18] (for mass 26), and Schwandt *et al.*[19] (for mass 39). The term $\sigma_{\mathrm{F}}(\mathrm{DWIA})$ is the "Fermi" ($\Delta J = 0$) part of the cross section; for the cases in Table I, it is nonzero only for the "mixed" ground-state-to-ground-state (g.s.-to-g.s.) transitions for the odd-A nuclei. We subtracted this estimate of the Fermi part of the cross section to obtain the exclusively Gamow-Teller part. This procedure should be quite reasonable; for pure Fermi (0^+ to 0^+ isobaric analog state) transitions we observed[20] that the DWIA normalizations are always close to unity, and for all cases in Table I $\sigma(\mathrm{DWIA}) >> \sigma_{\mathrm{F}}(\mathrm{DWIA})$.

The shell-model transition densities were obtained with the Cohen-Kurath "[8-16]POT" interaction[21] for the p shell and Wildenthal's interaction[22] for the sd shell. Values of $B(\mathrm{GT,free})$ are given in the first column under "theory" in Table I. The systematic quenching of the experimental $B(\mathrm{GT})$ values deduced from β decay relative to $B(\mathrm{GT,free})$ is apparent. For several cases in Table I the experimental values of $B(\mathrm{GT},\beta)$ and $B(\mathrm{GT},pn)$ are close to each other; however, there are some notable discrepancies, in particular the g.s.-to-g.s. transitions for $A = 13$, 15, and 39.

In Fig. 1 we present excitation energy spectra at 0° for the reactions ^{15}N$(p,n)^{15}$O and ^{39}K$(p,n)^{39}$Ca at 135 MeV. The K target was made from natural potassium, and contained a small amount of ^{41}K; the ^{15}N target was a gas cell with thin Kapton windows. Small contaminant peaks are identified in each spectrum. For

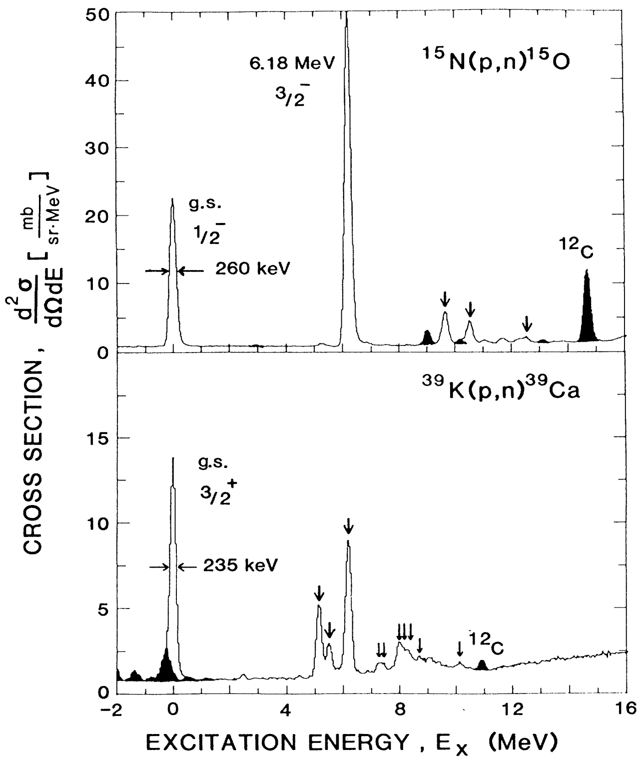

FIG. 1. Excitation-energy spectra for the reactions $^{15}N(p,n)^{15}O$ and $^{39}K(p,n)^{39}Ca$ at 135 MeV and 0°. The arrows indicate the locations of transitions with $\Delta L=0$ angular distribution which are known or presumed to be $1p_{3/2}$ ($1d_{5/2}$) hole states for ^{15}O (^{39}Ca). Shaded peaks are from contaminants.

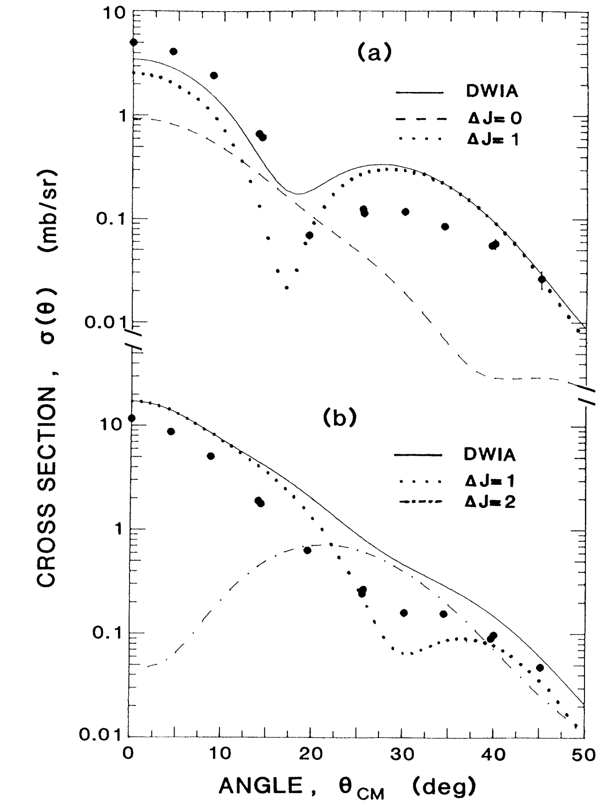

FIG. 2. Cross-section angular distributions for the reaction $^{15}N(p,n)^{15}O$ at 135 MeV, (a) for the ^{15}O g.s. and (b) for the ^{15}O 6.18-MeV state. The curves are DWIA calculations described in the text.

both targets, the g.s. transition carries essentially all of the $j=l-\frac{1}{2}$ hole strength; the $j=l+\frac{1}{2}$ hole strength is distributed among several states between 5 and 12 MeV of excitation. By careful peak fitting (with the peak locations fixed to reproduce the known spectra of states from complications in the literature), we identified four states in ^{15}O and ten states in ^{39}Ca with $\Delta L=0$ angular distributions, which we presume contain the large majority of the $j=l+\frac{1}{2}$ hole strength for these two targets. The strength in all of these states is included in Table I.

In Fig. 2 we present cross-section angular distributions for the $^{15}N(p,n)^{15}O$ reaction at 135 MeV, for transitions to the g.s. and to the 6.18-MeV state, along with the DWIA calculations (described above) with unit normalization. The 6.18-MeV state contains about 85% of the $p_{3/2}$ hole strength excited in this reaction. Note that the DWIA cross section for the 6.18-MeV state is larger than the data, whereas the DWIA cross section for the g.s. is smaller than the data. The reactions $^{15}N(p,n)^{15}O$(g.s.) and $^{13}C(p,n)^{13}N$(g.s.) are the only cases observed thus far for the medium-energy (p,n) reaction where DWIA cross sections are substantially smaller than the data. This result is clear in Table I; these are the only transitions where $B(\mathrm{GT},pn)$ is *"enhanced"* related to B(GT,free). This observation is in sharp contrast to Ref. 5, where the authors concluded from cross-section *ratios* that there is additional quenching in the $\frac{1}{2}^-$ to $\frac{3}{2}^-$ transitions. However, our observed quenching of the $\frac{1}{2}^-$ to $\frac{3}{2}^-$ transitions is typical for this mass region; it is the $\frac{1}{2}^-$ to $\frac{1}{2}^-$ transitions that are apparently anomalous.

In Ref. 4 the quenching for the *sd*-shell nuclei was parametrized in terms of a more general Gamow-Teller–type ($\Delta J=1$, $\Delta T=1$) operator which includes terms of the form $\mathbf{l}\tau_\pm$ and $\mathbf{p}\tau_\pm=(8\pi)^{1/2}[Y^{(2)}\otimes\mathbf{s}]^{\Delta J=1}\tau_\pm$. The single-particle matrix element $\langle j||(\delta_s\mathbf{s}+\delta_l\mathbf{l}+\delta_p\mathbf{p})\tau_\pm||j'\rangle$, can be expressed in the form $\delta(j,j')<j||\mathbf{s}\tau_\pm||j'\rangle$, where $\delta(j,j')=\delta(j',j)$, for cases where $\langle\,||\mathbf{s}\tau_\pm||\,\rangle$ is nonzero. The correction factors $\delta(j,j')$ [see Eq. (14) of Ref. 4] for the cases of interest are

$$\delta(j=l+\tfrac{1}{2},j'=l-\tfrac{1}{2})=\delta_s-\delta_l-\tfrac{1}{2}\delta_p,$$

$$\delta(p_{1/2},p_{1/2})=\delta_s-4\delta_l+4\delta_p,$$

$$\delta(d_{3/2},d_{3/2})=\delta_s-6\delta_l+2\delta_p,$$

$$\delta(d_{5/2},d_{5/2})=\delta_s+2\delta_l+\tfrac{4}{7}\delta_p.$$

The *sd*-shell $B(\mathrm{GT},\beta)$ values calculated with the empirical effective operator of Refs. 4 and 14 are given in the second column under "theory" in Table I. The relative constancy of the quenching as a function of mass occurs because $\delta_s >> \delta_l$ and $\delta_s >> \delta_p$; however, a nonzero δ_p is essential for the *L*-forbidden GT decay of ^{39}Ca (Adelberger *et al.*[23]). The empirical values of δ_l and δ_p agree well with those of Ref. 3, but the empirical value for δ_s is about 50% larger (see discussion in Ref. 4). The effective *p*-shell B(GT) values in Table I were obtained with δ parameters calculated by Towner and Khanna.[3,24]

The orbit dependence of the $\delta(j,j')$ values given above, and the disagreements between the experimental β-decay and (p,n) B(GT) values noted in Table I, show immediately that the δ_p parameter may be responsible. Note that δ_p is particularly important for the $p_{1/2}$ to $p_{1/2}$ transition in $A=15$. In the last column in Table I, we give the B(GT) values calculated with the same effective operator used for the β decay, except that the δ_p parameter was increased from $\delta_p=0.017$ to 0.09 (0.026 to 0.09) for the *sd* shell (*p* shell). The effective B(GT) values obtained with this simple modification agree generally with the (p,n) data. We can understand (1) the large enhancement of the $j=l-\frac{1}{2}$ to $j'=l-\frac{1}{2}$ transitions in $A=13$, 15, and 39, and (2) the small effect of δ_p for the strong $j=l+\frac{1}{2}$ to $j'=l-\frac{1}{2}$ transitions.

We note here that we observed a small 0° cross section for the 2.47-MeV state ($J^\pi=\frac{1}{2}^+$) of ^{39}Ca. This transition is L forbidden in β decay and has a small $B(\mathrm{GT},\beta)$.[23] The (p,n) cross section for this state, though small, yields a $B(\mathrm{GT},pn)\sim 100B(\mathrm{GT},\beta)$, as would be expected, given the larger value of δ_p for the (p,n) reaction.

What causes the enhancement of δ_p for the (p,n) reaction? The small but nonzero value of δ_p for β decay arises primarily from the Δ-isobar admixtures in the nuclear wave functions.[3] Thus we speculate that the enhancement for (p,n) reactions may be due to Δ-isobar admixtures in the reaction mechanism.

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