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Particle-hole strength excited in the $^{48}Ca(p,n)^{48}Sc$ reaction at 134 and 160 MeV: Gamow-Teller strength

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Gamow-Teller strength in the $^{48}Ca(p,n)^{48}Sc$ reaction was studied at 134 and 160 MeV. Neutron energy spectra were measured by the time-of-flight technique with resolutions of about 320 and 460 keV, respectively. The cross sections reported at 160 MeV are increased (by a factor of about 1.4) from results reported previously. The 1^+ Gamow-Teller strength is observed to be split into a low-lying state at $E_x = 2.52$ MeV, the Gamow-Teller giant resonance in a complex of states between 4.5 and 14.5 MeV, and a single $T=4$ state at 16.8 MeV. The general distribution of the 1^+ strength in ^{48}Sc is in good agreement with a shell-model prediction. The total 1^+ strength observed in discrete states amounts to 43% of the simple Gamow-Teller sum rule, relative to the observed 0^+, Fermi strength assumed to be concentrated into the isobaric analog state at 6.67 MeV. Consideration of the $\Delta l = 0$ contributions to the background under the Gamow-Teller giant resonance and of the non-quasifree scattering contributions to the continuum (up to about 30 MeV) increases this fraction to about 70%. Possible Gamow-Teller strength in the quasifree scattering contributions to the continuum is discussed.

I. INTRODUCTION

There is considerable current interest in the excitation of "Gamow-Teller" (GT) strength in nuclei via the (p,n) reaction at medium energies. Insofar as the (p,n) reaction proceeds predominantly via one-step processes, transitions to 1^+ states from even-even target nuclei must proceed via the isovector spin-transfer term of the nucleon-nucleon effective interaction. At low-momentum transfer (i.e., near 0°), these transitions excite strength similar to that of Gamow-Teller beta decays. Goodman *et al.*[1,2] confirmed that forward-angle (p,n) spectra are dominated by such spin-transfer transitions and showed that the cross sections to different final states are proportional to the squares of the corresponding GT matrix elements as determined from beta decay. The (p,n) measurements offer the possibility of extending the beta decay studies to excitation energies otherwise kinematically unavailable. For a target with a neutron excess, the (p,n) reaction can excite 1^+ states with isospin equal to that of the target nucleus ($T_0=4$ for ^{48}Ca), or with isospin one less ($T_0-1=3$) or one greater ($T_0+1=5$) than that of the target. Both of the lower-isospin components are observed in the 1^+ spectrum of ^{48}Ca. This 1^+ strength, which is excited via the spin-transfer, isospin-transfer, central term of the effective interaction, represents a relatively simple excitation from the target nucleus and should be amenable to description by current nuclear structure calculations. In an earlier paper[3] we showed that the relative distribution of 1^+ strength is in good agreement with a shell-model prediction;[4] however, the total amount of 1^+, GT strength appears to be considerably less than expected in comparison with either theoretical estimates or with respect to the "Fermi" strength observed in the isobaric analog state (IAS) transition. Goodman *et al.*[2,5] reported similar "missing" GT strength for other medium-mass nuclei. This missing strength is sometimes interpreted[6-9] to be evidence for the excitation of Δ isobars with the (p,n) reaction. Osterfeld[10] reported that microscopic distorted-wave-impulse-approximation (DWIA) calculations indicate that some of this missing GT strength in the $^{48}Ca(p,n)^{48}Sc$ reaction may reside in part of the background subtracted underneath the $T=3$ complex of 1^+ states observed in the experimental spectra. Bertsch and Hamamoto[11] reported that extended shell-model calculations including two-particle, two-hole configurations indicate that a substantial amount of the GT strength will be moved into the nuclear continuum up to about 45 MeV of excitation. Both of these possibilities are considered here for the $^{48}Ca(p,n)^{48}Sc$ reaction. A new estimate of the total observed GT strength is presented and discussed.

II. EXPERIMENTAL MEASUREMENTS

Neutron energy spectra were measured by the time-of-flight technique with the beam-swinger facility[12] at the Indiana University Cyclotron Facility. Overall energy resolutions of about 320 and 450 keV were obtained in the 135 and 160 MeV experiments, respectively. The experimental procedure and data reduction are described in detail in the preceding companion paper.[13] The 0° neutron

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excitation-energy spectrum at 134 MeV is shown in Fig. 1. The 0° spectrum at 160 MeV was presented earlier.[3] Cross sections for various transitions were extracted from measured geometrical factors, target thickness, and beam integration and calculated neutron detection efficiencies. The detector efficiencies were calculated with a Monte Carlo neutron transport code[14] and checked by comparison of (p,n) and (p,p′) analog-state reaction cross sections.[15,16]

Note that the 160 MeV cross sections presented here differ by about 40% from those presented earlier.[3] This difference occurs because of an inadvertent omission (in the earlier results) of the correction for the neutron attenuation in a 2.22 cm thick copper plate which was used in the 160 MeV measurements to ensure that charged particles from the target could not be detected by the neutron counters. Since the charged-particle anticoincidence detectors were only 0.6 cm thick in the 160 MeV experiment and could possibly be $<100\%$ efficient, the copper plate was used (only) for the 160 MeV measurements to ensure that energetic protons did not leak through the anticoincidence detector. Neutron attenuation in the copper plate was neglected only in the paper of Anderson *et al.*[3] [The later paper by Watson *et al.*[17] reporting the observation of the "0 $\hbar\omega$," 7^+ state excitation in the ^{48}Ca(p,n)^{48}Sc reaction *did* include a correction for the neutron attenuation in the copper plate.] No other experimental results reported by the various Kent State University collaborations are affected by this correction.

There remains a discrepancy of approximately 30% between some cross sections reported by this group and other (p,n) experimental measurements including the ^{48}Ca(p,n)^{48}Sc reaction[18] performed at the Indiana University Cyclotron Facility (IUCF). The differences are almost certainly due to the different techniques adopted for determining neutron detector efficiencies. Basically, this group uses calculated detector efficiencies which are checked by comparison of analog (p,n) and (p,p′) cross section measurements. The other experimenters used the ^{7}Li(p,n)^{7}Be(g.s. + 0.435 MeV) reaction to measure their neutron detector efficiencies. They obtained their efficiencies by comparing their measured (angle-integrated) (p,n) cross sections for this reaction with an independent measurement[19] which observed the decay of these two states back to ^{7}Li (by electron capture). Through a careful analysis of our calculated efficiencies and (p,n) vs (p,p′) analog-state comparisons (see the companion paper and especially Ref. 16 for more detailed discussions of these analyses), we became convinced that there must exist some error associated with the Li-activation technique as performed originally by the other experimenters. It turns out[20] that the Li-activation measurements need to be corrected for ^{7}Be production by spallation reactions on the chlorine present in the LiCl targets used for the original measurements. The magnitude of the correction is enough ($\sim 20\%$) to resolve the discrepancy between the different techniques.

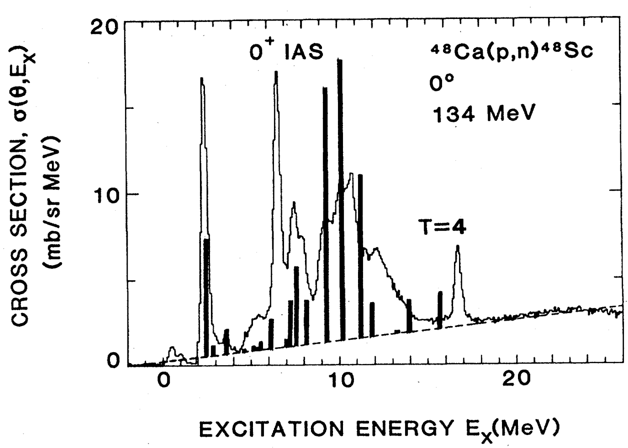

FIG. 1. Comparison of the experimental neutron excitation-energy spectrum for the 134 MeV ^{48}Ca(p,n)^{48}Sc reaction at 0° with DWIA calculations of the 1^+ spectrum in ^{48}Sc with $1f$-$2p$ shell model wave functions. See the text for details of the calculations.

III. GAMOW-TELLER STRENGTH IN DISCRETE STATES

In addition to the $(f_{7/2},f_{7/2}^{-1})$ particle-hole band of states observed at low excitation energies in ^{48}Sc, and discussed in the companion paper,[13] the (p,n) measurements show a strong excitation of a complex of states between about 5 and 14 MeV of excitation in the forward-angle spectra. This strength, along with the separate transitions to states observed at $E_x = 2.52$ and 16.8 MeV, were interpreted earlier[3] as 1^+ excitations in ^{48}Sc. The distribution and relative strength of these 1^+ excitations were shown[3] to agree well with a prediction by Gaarde *et al.*[4] of the 1^+ spectrum in ^{48}Sc.

A. Comparison with DWIA calculations using shell-model wave functions

In Fig. 1, we show a comparison of the experimental 0° spectrum at 134 MeV with the 1^+ spectrum calculated in the distorted wave impulse approximation (DWIA) with $1f$-$2p$ shell-model wave functions.[13] (These shell-model calculations are similar to those of Gaarde *et al.*[4] used in the earlier comparisons at 160 MeV only.) The calculations are based on the $1f$-$2p$ interaction of Van Hees and Glaudemans,[21] but with the $1f_{7/2}$-$1f_{5/2}$ splitting increased by 2 MeV as discussed below. These shell-model calculations were used also in the analyses of the $(f_{7/2},f_{7/2}^{-1})$ particle-hole band of the companion paper. The shell-model calculations include the configurations $(\pi f_{7/2},\nu f_{7/2}^{-1})$, $(\pi f_{5/2},\nu f_{7/2}^{-1})$, and $(\pi f_{7/2},\nu f_{7/2}^{-2})$ plus a neutron excited into the $2p_{3/2}$, the $2p_{1/2}$, or the $1f_{5/2}$ orbit. For the last series of configurations, the excited neutron is allowed to couple with all possible J values of the seven nucleons left in the $f_{7/2}$ orbit. This basis yields 20 states with $J^\pi = 1^+$; 19 of these 20 states have isospin $T=3$, and only one $T=4$. The $T=4$ level is predicted to lie 1.3 MeV above the highest $T=3$ level. For the strength calculation presented in Fig. 1, it is assumed that only the 1p-1h components [viz., the $(\pi f_{7/2},\nu f_{7/2}^{-1})$ and $(\pi f_{5/2},\nu f_{7/2}^{-1})$ configurations] of these states are excited via the (p,n) reaction. Thus the strength calculations use only these two configurations, but with the amplitudes provided by the full shell-model calculation. A DWIA calculation with the code DWBA 70 (Ref. 22) uses these amplitudes, plus the global optical-model parameters of Schwandt *et al.*[23] and the 140 MeV nucleon-nucleon effective interaction of Love and Franey.[24] We used a fixed set of radial wave functions which were chosen to reproduce the single-particle separation energies between ^{47}Ca, ^{49}Ca, and ^{49}Sc, relative to ^{48}Ca. The results of these calculations are shown as the vertical bars in Fig. 1.

The comparison of the predicted 1^+ spectrum with the experimental 0° spectrum is seen to be remarkably good. The excitation energies of the predicted spectrum were shifted down by 0.3 MeV in order to align the lowest 1^+ state with the observed state at $E_x=2.52$ MeV. The general distribution of the complex of states between $5 \leq E_x(\mathrm{MeV}) \leq 14$ is predicted reasonably well. The only adjustment made to the $1f$-$2p$ shell interaction of Van Hees and Glaudemans to obtain this fit was to increase the $f_{7/2}$-$f_{5/2}$ level splitting by 2 MeV. Without this adjustment, the $T=4$, 1^+ state is predicted to lie ~2 MeV lower in excitation energy than observed, and the distribution of 1^+ strength in the Gamow-Teller giant resonance (GTGR) is poorly reproduced. This adjustment is probably required because the original interaction was fit to nuclear levels in heavier nuclei, with more total nucleons in the $1f$-$2p$ shell. These levels need not be identical in $A=48$, which just begins to fill the $1f$-$2p$ shell.

The good agreement between these predictions and the measured spectrum verifies that the dominant structure of these states is described correctly in the calculations. Thus, the low-lying state at $E_x=2.52$ MeV is predominately $(f_{7/2},f_{7/2}^{-1})$, the high-lying state at $E_x=16.8$ MeV is plausibly $T=4$, and the complex of strength in between is a $T=3$ admixture of the various configurations assumed in the basis. Thus, the strongly-excited complex of states between 4.5 and 14.5 MeV is the GTGR for this reaction. The $T=4$ assignment for the 16.8 MeV state is confirmed by the observations of the "parent" 1^+ state at $E_x=10.2$ MeV in ^{48}Ca via (e,e′) and (p,p′) excitations.[25–28] (Excitation energies in ^{48}Sc correspond to excitation energies in ^{48}Ca offset by approximately the excitation energy of the 0^+, IAS at $E_x=6.67$ MeV; thus, a 1^+ state observed at 10.2 MeV in ^{48}Ca would be expected near 16.9 MeV in ^{48}Sc, in good agreement with the state observed at 16.8 MeV.)

Shown in Figs. 2 and 3 are the experimental angular distributions for the transition to the 1^+ states at $E_x=2.52$ and 16.8 MeV, respectively. Shown in Fig. 4 is the experimental angular distribution for the GTGR complex of states. Excluded here is the contribution from the 0^+, IAS at 6.67 MeV. The fitting of this GTGR complex was shown and discussed in the preceding companion paper.[13]

The experimental angular distributions are compared with DWIA calculations for these 1^+ transitions. The calculations are the same as those described above for the comparisons of the 0° spectrum shown in Fig. 1. The cal-

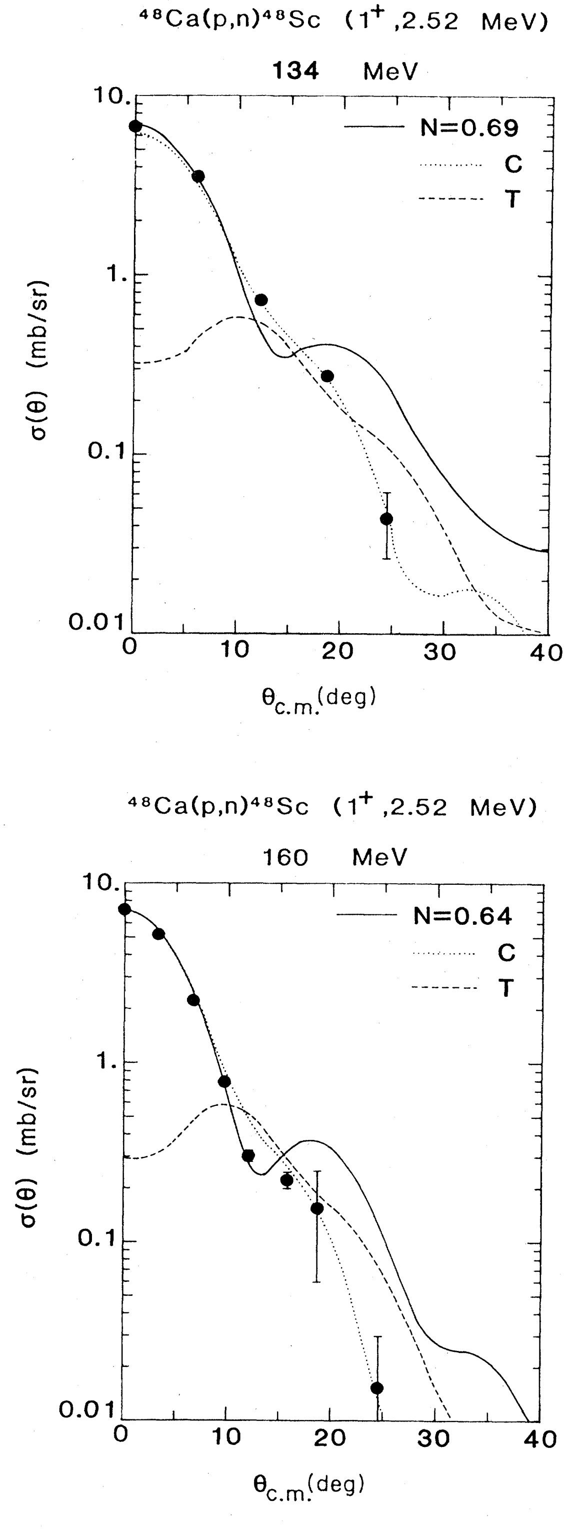

FIG. 2. Experimental angular distributions at (a) 134 and (b) 160 MeV for the ^{48}Ca(p,n)^{48}Sc reaction to the 1^+, 2.52 MeV state. The curves represent DWIA calculations as described in the text. The error bars (here and in the subsequent figures) represent the uncertainties provided by the fitting code only and are primarily statistical (see the text).

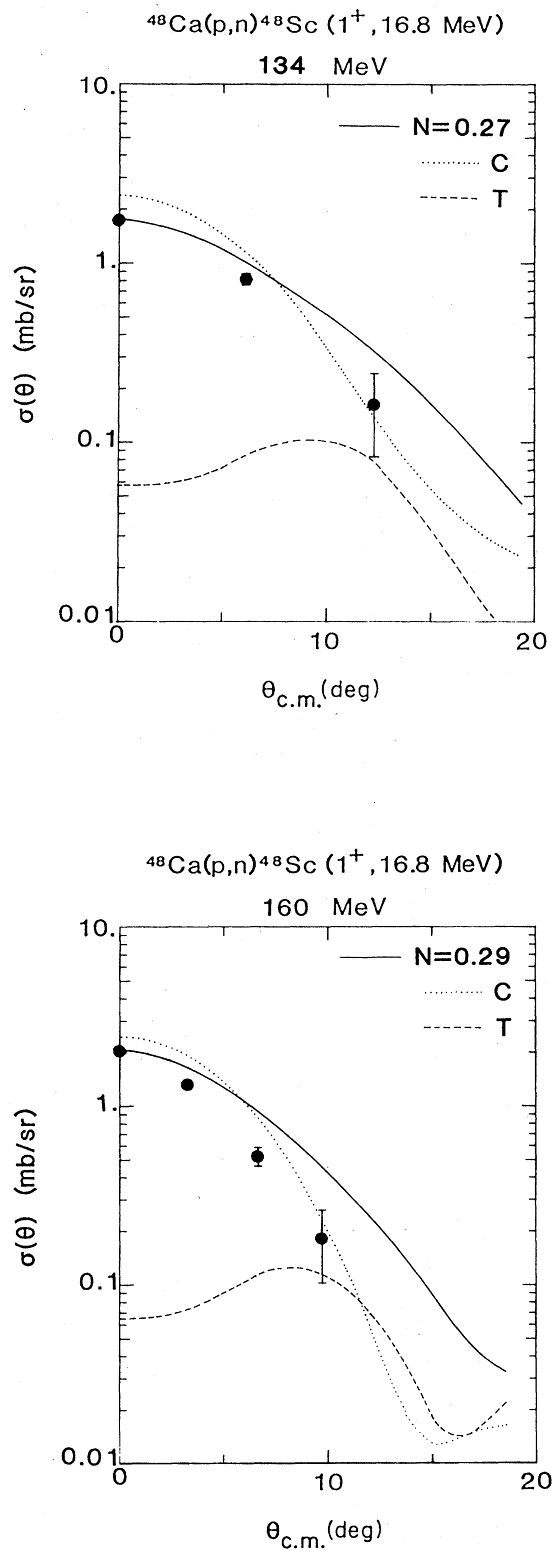

FIG. 3. Experimental angular distributions at (a) 134 and (b) 160 MeV for the ^{48}Ca(p,n)^{48}Sc reaction to the $T=4$, 1^+, 16.8 MeV state. The curves represent DWIA calculations as described in the text.

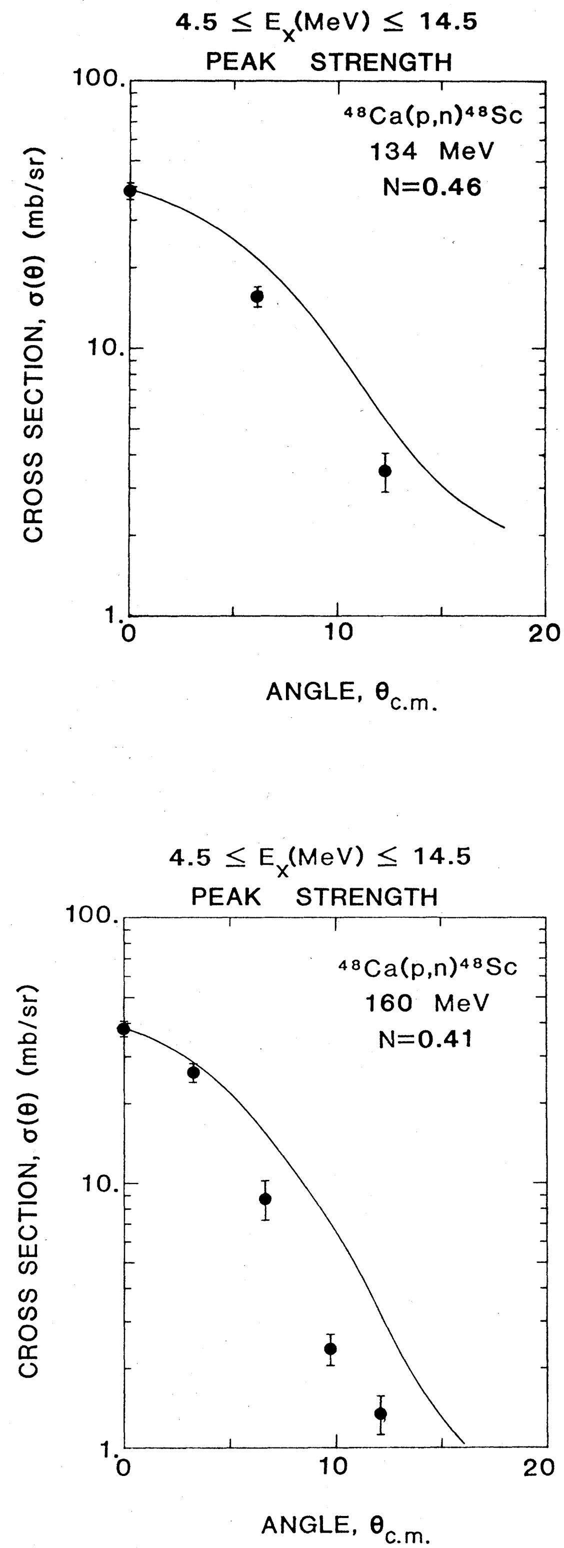

FIG. 4. Experimental angular distributions at (a) 134 and (b) 160 MeV for the ^{48}Ca(p,n)^{48}Sc reaction exciting the Gamow-Teller giant resonance (GTGR) complex of states at excitation energies between $4.5 \leq E_x(\mathrm{MeV}) \leq 14.5$. The curves represent DWIA calculations as described in the text.

culated angular distribution of the GTGR complex is the sum of the separate calculations for the 18 $T=3$, 1^+ states predicted to lie in this excitation-energy region. The background subtracted in this region was shown in the fitted time-of-flight (TOF) spectrum presented in the preceding paper and is shown also as the dashed line in Fig. 1. The shapes are seen to be peaked strongly at 0° for all three of these angular distributions, and are described reasonably well by the calculated angular distributions. Note that the angular distribution for only the 2.52 MeV state can be extracted reliably beyond about 12°. The GTGR complex of states between 4.5 and 14.5 MeV is interfered with by states of other spins and parities at wider angles (see the excitation energy spectra presented in the companion paper). The 16.8 MeV state is relatively weak and sits on a large continuum, which makes it difficult to observe except at the most forward angles.

The normalization required for the comparisons of the DWIA calculations with the three 1^+ angular distributions are seen to be 0.69, 0.46, and 0.27 for the transitions to the 2.52 MeV state, the GTGR complex, and the 16.8 MeV state, respectively. We note that the states in ^{48}Sc become unbound to proton emission at $E_x=9.4$ MeV and that the DWIA calculations do not take into account the fact that states above this excitation energy have very different wave functions from bound states; nevertheless, it is clear that the total *peak* cross section observed for these 1^+ excitations is only about 48% of that predicted by the DWIA calculations.

B. Comparison with the observed "Fermi" strength

It is possible to estimate also whether or not we are seeing all of the 1^+ strength expected for this reaction by comparison with the 0^+ strength observed in the IAS at 6.67 MeV. At energies greater than about 100 MeV, the (p,n) reaction is believed to proceed between the initial state and the final state predominately via one-step processes; hence, the cross section for a specific transition is directly proportional to the square of the matrix element between the initial- and final-state wave functions connected by the appropriate term (or terms) in the nucleon-nucleon effective interaction which can produce the transition considered. For a 0^+ to 0^+ transition, the appropriate term is the isospin-transfer term $V_\tau(r)(\tau_i\cdot\tau_p)$. For a 0^+ to 1^+ transition, the appropriate term is the spin-transfer, isospin-transfer term $V_{\sigma\tau}(\mathbf{r})(\sigma_i\cdot\sigma_p)(\tau_i\cdot\tau_p)$. In the limit of zero momentum transfer, and given the short-range nature of $V_\tau(r)$ and $V_{\sigma\tau}(r)$, these two kinds of transitions become essentially the same as Fermi and Gamow-Teller transitions in beta decay. Although a (p,n) reaction at 0° does not actually occur at zero momentum transfer, the correspondence between (p,n) cross sections and Fermi and Gamow-Teller types of beta decays was shown[1,2] to be valid for several different cases. If we assume this correspondence is valid in this case, we can use the standard sum rules[4] for Fermi and Gamow-Teller strength in nuclei, viz.,

$$S_{\beta^-}(\mathrm{F})-S_{\beta^+}(\mathrm{F})=(N-Z)$$

where

$$S_{\beta^\pm}(\mathrm{F})=\sum_f\left|\left\langle f\left|\sum_k\tau_k^\pm\right|i\right\rangle\right|^2,$$

and

$$S_{\beta^-}(\mathrm{GT})-S_{\beta^+}(\mathrm{GT})=3(N-Z)$$

where

$$S_{\beta^\pm}(\mathrm{GT})=\sum_f\left|\left\langle f\left|\sum_k\sigma_k\tau_k^\pm\right|i\right\rangle\right|^2.$$

We expect that the β^+ strength is small because it would have to come from correlations in the ^{40}Ca core; in this case, the total β^- strength should be

$$S_{\beta^-}(\mathrm{F})=B(\mathrm{F})=(N-Z) \tag{1}$$

and

$$S_{\beta^-}(\mathrm{GT})=B(\mathrm{GT})\gtrsim 3(N-Z)\,. \tag{2}$$

Now we can use these results to predict a ratio between the 1^+ (GT) strength and the 0^+ (Fermi) strength expected for the ^{48}Ca(p,n)^{48}Sc reaction. Gamow-Teller strength is related to cross section through a proportionality factor which can be determined only if there exists a measured analog β decay. Unfortunately, no such analog decay is available for calibrating the ^{48}Ca(p,n)^{48}Sc(1^+) transitions. Nevertheless, as long as we compare the ratio of observed 1^+ cross section strength to the 0^+ cross section strength, we will obtain a measure of the observed GT strength *relative* to the observed Fermi strength. The 0° (p,n) cross sections can be written in the factorized distorted-wave impulse approximation as[29]

$$\sigma_{\mathrm{F}}(0^\circ)\simeq 8\pi N_D(\mathrm{F})\left[\frac{\mu}{2\hbar^2}\right]^2\left[\frac{k_f}{k_i}\right]B(\mathrm{F})\,|V_\tau|^2 \tag{3}$$

and

$$\sigma_{\mathrm{GT}}(0^\circ)\simeq 8\pi N_D(\mathrm{GT})\left[\frac{\mu}{2\hbar^2}\right]^2\left[\frac{k_f}{k_i}\right]B(\mathrm{GT})\,|V_{\sigma\tau}|^2\,. \tag{4}$$

Thus the expected ratio becomes

$$R=\frac{\sigma_{\mathrm{GT}}(0^\circ)}{\sigma_{\mathrm{F}}(0^\circ)}=\frac{N_D(\mathrm{GT})}{N_D(\mathrm{F})}\frac{k_f^{\mathrm{GT}}}{k_f^{\mathrm{F}}}\frac{B(\mathrm{GT})}{B(\mathrm{F})}\left|\frac{V_{\sigma\tau}}{V_\tau}\right|^2. \tag{5}$$

Using Eqs. (1) and (2) above, we have

$$R=3\frac{N_D(\mathrm{GT})}{N_D(\mathrm{F})}\frac{k_f^{\mathrm{GT}}}{k_f^{\mathrm{F}}}\left|\frac{V_{\sigma\tau}}{V_\tau}\right|^2. \tag{6}$$

Now for (p,n) transitions with available analog beta-decay results, Taddeucci *et al.*[30] determined the ratio

$$\frac{N_D(\mathrm{GT})}{N_D(\mathrm{F})}\left|\frac{V_{\sigma\tau}}{V_\tau}\right|^2\simeq\left[\frac{E_{\mathrm{p}}}{(54.9\pm0.9)}\right]^2. \tag{7}$$

Thus, for $E_{\mathrm{p}}=134$ MeV,

$$R\cong(3)(6.0)\frac{k_f^{\mathrm{GT}}}{k_f^{\mathrm{F}}}\,. \tag{8}$$

Finally, if we take k_f^{GT} at the centroid of the observed GT (1^+) strength (viz., $\sim E_x = 10$ MeV), and k_f^{F} for the IAS at $E_x = 6.7$, we find $(k_f^{\mathrm{GT}}/k_f^{\mathrm{F}}) = 0.96$. Hence, we might expect

$$R \cong (3)(6.0)(0.96) = 17.3 .$$

This result requires that the GT and Fermi cross sections be compared at the same momentum transfer. Because the momentum transfer at 0° varies with excitation energy in the residual nucleus, the requirement is not satisfied. In order to compare the observed GT strength with the Fermi strength assumed to be concentrated in the IAS, comparisons must be performed at the same momentum transfer. For each case, the GT transition was extrapolated to the same momentum transfer value as that for the IAS transition at 0°. For the 1^+, 2.52 MeV state, the 1^+ cross section was taken at the appropriate angle (greater than zero) to be at this same momentum transfer. The 2.52 and 16.8 MeV 1^+ momentum-transfer distributions were observed to have the same shape at small momentum transfers. Thus, the shape of the 2.52 MeV transition was used to extrapolate into the required (low) value of momentum transfer. These corrections were found to vary from -4% for the 2.52 MeV strength to $+22\%$ for the 16.8 MeV strength. The total GT strength observed in the 2.52-MeV state, the GTGR (from 4.5 to 14.5 MeV) and the 16.8 MeV state is found to be 50.7 mb/sr (see Table I). Thus, we have,

$$R_{\mathrm{expt}} = \frac{\Sigma\sigma(1^+)}{\sigma(0^+,\mathrm{IAS})} = \frac{50.7\ \mathrm{mb/sr}}{6.9\ \mathrm{mb/sr}} = 7.35$$

which, by these arguments, is 43% of that expected from the simple sum rules.

It is somewhat reassuring that the comparison of the ratio of GT to Fermi strength yields approximately the same fraction as found in the comparison of the total observed 1^+ strength with the DWIA predictions, discussed earlier. These results are similar to those observed for other studies of 1^+, GT strength in other medium- and heavy-mass nuclei.[2,5,31] This agreement between the two methods is not really surprising since the nuclear structure calculations assume the initial state consists of neutrons only (outside a closed ^{40}Ca core) and the total 1^+ strength calculated must satisfy the same simple sum rule for GT strength as assumed in the above analysis. In fact, the only real differences in the two methods are (1) that the second method compares directly with the *observed* Fermi strength and (2) uses an *empirically* determined ratio for the strengths of the GT and Fermi terms in the N-N effective interaction. The first method uses the Love and Franey N-N effective interaction to compare the GT and Fermi strengths separately. Because the agreement between the observed and calculated Fermi strengths is so good in the first method (only 7% difference in cross section magnitudes—see the companion paper), and because the ratio of GT to Fermi strength ($V_{\sigma\tau}/V_\tau$) in the N-N effective interaction of Love and Franey agrees with the empirically determined ratio to above 140 MeV, the two different methods give about the same result. In fact, if one renormalizes the DWIA calculations to agree in magnitude with the experimental measurements for the Fermi (IAS) strength, then two-thirds of the 10% difference in the two methods is removed.

TABLE I. Summary of Gamow-Teller and Fermi cross sections observed at 135 MeV. Ratio $= \Sigma$GT/F $= \sim 82/6.9 = \sim 11.9$, which is $\sim 69\%$ of the simple sum-rule ratio of 17.3 (see the text).

E_x (MeV)	Fermi (F)	σ (0°) (mb/sr) Gamow-Teller (GT)	GT corrected[a]
6.67	6.9		
2.52		6.8	6.5
4.5–14.5		38.7	42.0
16.8		1.8	2.2
Total GT cross section in discrete states		47.3	50.7
Background (4.5–14.5)		~ 13	~ 14
Continuum (14.5–30)		~ 12	~ 17
Total GT cross section			~ 82

[a]Adjusted so that comparison with Fermi cross section (assumed to be in IAS) is performed at the same momentum transfer (see the text).

IV. GAMOW-TELLER STRENGTH IN THE CONTINUUM

The above analyses of the experimentally observed 1^+ strength do not attempt to estimate any contributions from possible 1^+ strength in either the background under the 4.5–14.5 MeV GTGR complex or in the nuclear continuum above this complex. Recently, Osterfeld[10] estimated the 1^+ strength in the underlying background. His microscopic calculations consider transitions to bound, quasibound, and unbound final states of (essentially) all possible spin and parities which can be reached in one-step mechanisms via particle-hole doorway states. These calculations indicate that the majority of the background under the GTGR complex is probably 1^+ strength. Also, Bertsch and Hamamoto[11] reported that a perturbative calculation indicates that two-particle, two-hole correlations in the target wave function will cause a significant amount [$\sim 30\%$ for ^{90}Zr(p,n)] of the GT strength to be moved up into the nuclear continuum at excitation energies from 10 to 45 MeV. Based on these recent theoretical indications, we considered the possibility that there may be additional 1^+ strength in the "experimenter's background" and in the continuum of the ^{48}Ca(p,n)^{48}Sc spectrum at 0°, which are not included in the peak areas extracted as discussed above.

As a starting point in considering possible GT strength in the background and continuum, it is appropriate to compare the ^{48}Ca(p,n) and ^{40}Ca(p,n) spectra at 0°. In the simple shell model, ^{40}Ca is a closed-shell nucleus with all $l-\frac{1}{2}$ and $l+\frac{1}{2}$ orbital partners filled. Thus one would not expect to see strong GT (i.e., $\Delta l = 0$, spin-transfer) transitions in the ^{40}Ca(p,n)^{40}Sc reaction; on the other hand, in the simple shell model, ^{48}Ca has eight excess neutrons in the $f_{7/2}$ orbit, which can participate in GT transitions, either to the $(\pi f_{7/2}, \nu f_{7/2}^{-1})$ configuration or to the

$(\pi f_{5/2}, \nu f_{7/2}^{-1})$ configuration. The two experimental 0° spectra are compared in Fig. 5. The ^{40}Ca(p,n) spectrum is shifted by the difference in the known Q values of the two reactions so that emitted neutrons of the same energies are aligned in the two spectra. As expected, the ^{48}Ca(p,n) spectrum shows considerable yield at energies above the kinematic cutoff for ^{40}Ca(p,n) which is due to the eight excess neutrons in ^{48}Ca. Also one sees that the continuum is much more strongly excited in the ^{48}Ca(p,n) reaction than the ^{40}Ca(p,n) reaction; note, however, that at least one of the three distinct peaks observed in the ^{40}Ca(p,n)^{40}Sc reaction [viz., the peak seen at a neutron energy T of 116 MeV (actually at $E_x = 2.6$ MeV in ^{40}Sc)] is probably a 1^+ state,[43] which indicates that *some* GT strength is excited in the ^{40}Ca(p,n)^{40}Sc reaction, as a result of ground-state correlations.

In order to try to understand the differences seen in the strength of the continuum excitations for these two reactions, we compared the spectra with plane-wave-impulse-approximation (PWIA) calculations for the (p,pn) quasifree neutron knockout reactions on ^{40}Ca and ^{48}Ca. In earlier work,[32] based on the comparison of (p,n) and (p,p′) inclusive spectra at $T_p = 90$ MeV, we showed that the high-energy portions of forward-angle spectra are likely dominated by these quasifree scattering (QFS) contributions. The ratio of the emitted neutron and proton spectra was observed (in Ref. 32) to be consistent with the ratio expected from QFS, and the high-energy portions of the spectra were observed to decrease with increasing angle generally as indicated by the QFS calculations. The wide-angle and lower-energy portions of the neutron and proton continua were observed to deviate substantially from the QFS predictions and require reaction-model descriptions which include multiple-scattering contributions.

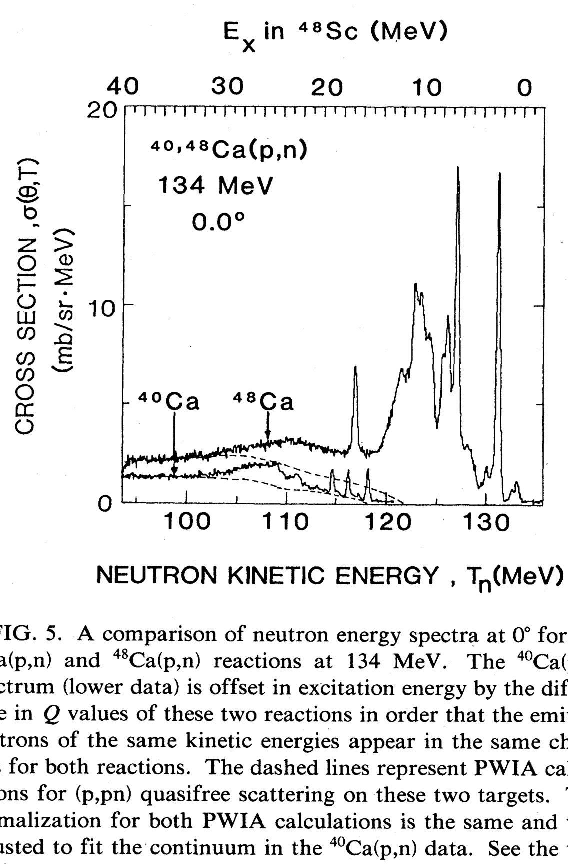

FIG. 5. A comparison of neutron energy spectra at 0° for the ^{40}Ca(p,n) and ^{48}Ca(p,n) reactions at 134 MeV. The ^{40}Ca(p,n) spectrum (lower data) is offset in excitation energy by the difference in Q values of these two reactions in order that the emitted neutrons of the same kinetic energies appear in the same channels for both reactions. The dashed lines represent PWIA calculations for (p,pn) quasifree scattering on these two targets. The normalization for both PWIA calculations is the same and was adjusted to fit the continuum in the ^{40}Ca(p,n) data. See the text for further details.

In Fig. 5 we show the results of PWIA quasifree scattering (QFS) calculations for both targets. The calculations were performed with the code developed by Wu[33] based upon the formula originally obtained by Wolff.[34] The calculation uses free nucleon-nucleon scattering cross sections and performs integrations over all possible momenta and angles of the scattered proton. There is a summation over all the single particle states each weighted by the number of nucleons in that state. The single-particle wave functions are generated by a subroutine[35] with binding energies obtained from neutron knockout measurements[36] and potentials obtained from Elton and Swift.[37] The QFS calculations were normalized to fit through the ^{40}Ca(p,n) continuum near $T = 95$ MeV. A normalization factor of ~ 0.2 is required to fit both of the 0° spectra simultaneously. Because these are plane-wave calculations, some normalization is certainly required. The code DWBA 70 was used to estimate a distortion factor of ~ 0.3 for these reactions (at 135 MeV) from the ratio of DWIA to PWIA calculations. Because the QFS calculations do not take into account Pauli-blocking effects, one expects the normalization factor will be even smaller than the simple distortion estimates at small angles. In fact, we do find that a normalization factor of about 0.3 is required to make the QFS calculations agree with the data at wider angles, viz., from about 20° to 40°. The important point is that the magnitude of the ^{48}Ca(p,n) continuum near $E_x = 35$ MeV is fit simultaneously with the *same* normalization factor as that required for ^{40}Ca(p,n). Thus, the QFS calculations indicate that the rather large difference observed in this high-energy part of the continuum is due simply to QFS on the eight excess neutrons in ^{48}Ca. Note also that the ^{40}Ca(p,n) spectrum is described rather well by the QFS calculation. The discrete peaks observed at low-excitation energies are clearly states in ^{40}Sc and are not expected to be described by QFS to ^{39}Ca. The broad peak seen near $E_x \approx 25$ MeV apparent excitation energy in ^{48}Sc($E_x \approx 10$ MeV in ^{40}Sc) is likely the collective $\Delta l = 1$ $(0^-, 1^-, 2^-)$ giant resonance in ^{40}Sc. (This broad peak is seen to dominate the spectrum near $\theta = 12°$.)

It should be noted that the QFS "background" calculations presented here are similar in shape and magnitude to the microscopic DWIA calculations by Osterfeld.[10] This similarity is not surprising since the microscopic calculations consider all reactions to proceed through the QFS channel as a "doorway" state. Thus, both sets of calculations have kinematic cutoffs (e.g., $E_x = 12$ MeV in ^{48}Sc) determined by the separation energies of the least tightly bound neutrons in ^{40}Ca and ^{48}Ca. The microscopic calculations have the advantage that they can explicitly indicate possible 1^+ strength excited in the continuum [starting from $(\nu f_{7/2})^8$ for the ^{48}Ca target nucleus]. The QFS calculations presented here have the advantage primarily that they are simple to perform and interpret. Since neither set of calculations includes nuclear collectivity, neither reproduces the $\Delta l=1$ peak observed in the continua near $T_n=110$ MeV. Note also that the microscopic calculations of Osterfeld would describe the continuum of ^{48}Ca(p,n) with *no normalization factor,* if he had not renormalized our (corrected) results[38] to use the normalization of Gaarde *et al.*[18] This renormalization is indicated here (see Sec. II) to be unwarranted. Thus, Osterfeld's calculations verify that the QFS calculations presented here do provide a reasonable estimate of the shape of the background and that this background should account for most of the strength of the continuum above about $E_x=30$ MeV (in ^{48}Sc).

At least for now, let us say that we do *not* want to consider the QFS contributions in our search for possible 1^+ GT strength in the ^{48}Ca(p,n) reaction; specifically, the (p,pn) reaction (i.e., QFS) proceeds to states in ^{47}Ca, rather than ^{48}Sc. Basically, the problem is that not all the $\Delta l=0$ contributions in the entire continuum will be GT strength. The reason is that if the continuum has large contributions from QFS, then the nucleon-nucleon (N-N) interaction is no longer restricted to the $V_{\sigma\tau}$ (or "Gamow-Teller") term, and will involve the V_τ (or "Fermi") term as well; furthermore, QFS will not be restricted to isovector terms of the N-N effective interaction. Our procedure is to begin by subtracting the QFS contributions from the continuum and then to perform a multipole decomposition of the remaining strength. The $\Delta l=0$ contribution of this remaining strength is, to first order, GT strength. We then must return to the QFS contributions and try to estimate what fraction might also be GT strength.

If we subtract the QFS calculations shown in Fig. 5 from the ^{48}Ca(p,n) spectrum, the resulting spectrum has a continuum decreasing to zero near $E_x=30$ MeV. This spectrum would still include a broad peak near $E_x=25$ MeV which is probably the collective $\Delta l=1$ resonance for this reaction (and is peaked near 10°). Thus, certainly not all of the strength observed in the continuum, after subtracting QFS contributions, is $\Delta l=0$ (1^+); therefore, we have extracted an angular distribution of the continuum from $E_x=14.5$ to 30 MeV in order to determine the $\Delta l=0$ contributions in this "residual" continuum. [The QFS backgrounds subtracted at the wider angles were determined also by fitting to the observed ^{40}Ca(p,n) spectrum near a neutron energy of 90 MeV.] The resultant angular distribution is shown in Fig. 6. A "multipole" decomposition of this angular distribution was then performed by fitting calculated DWIA angular distributions for $\Delta l=0$, 1, and 2 transitions to the experimental results. The $\Delta l=0$ DWIA angular distribution was assumed to have the shape of the transition to the $T=4$, 1^+ state at 16.8 MeV. The $\Delta l=1$ angular distribution was taken as the calculated shape for the sum of the four possible (single-step) $\Delta l=1$ transitions in this reaction, viz., 0^+ to 0^-, 0^+ to 1^- (with and without spin flip), and 0^+ to 2^-. (Note that the 0^+ to 2^- DWIA calculations include some strength from $\Delta l=3$ contributions.) The final states were described as the coherent-state wave functions for these transitions in a particle-hole basis using both the *s*-*d* and *f*-*p* shells (14 possible p-h configurations). The calculated shape for a $\Delta l=2$ transition was simply assumed to be for a 3^+ state, assuming $\Delta l=2$ plus spin transfer (the separation of $\Delta l=0$ and 1 near 0° is not sensitive to this shape). The $\Delta l=0$, 1, and 2 shapes obtained from these calculations are shown in Fig. 6, with individual normalization factors adjusted to fit the experimentally observed angular distribution for the residual continuum.

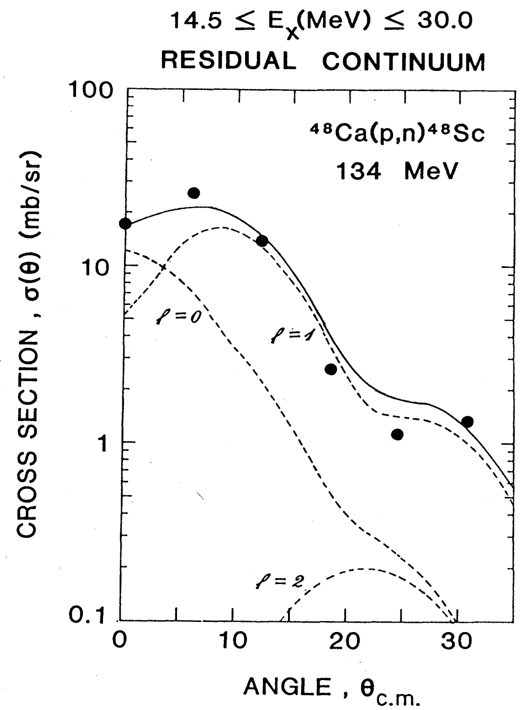

FIG. 6. Experimental angular distribution for the continuum region with excitation energies between $14.5<E_x(\text{MeV})\leq 30$ for the ^{48}Ca(p,n)^{48}Sc reaction after subtracting the calculated quasifree scattering contributions (see Fig. 5 and the text). The curves represent DWIA calculations for $\Delta l=0$, 1, and 2 transitions and were normalized to provide the best overall fit to the experimental angular distribution. See the text for further details.

The experimental angular distribution [for $14.5<E_x(\text{MeV})<30$] is seen to be described reasonably well by the multipole fits described above. These fits indicate that the fraction of the 0° residual continuum which must be ascribed to the $\Delta l=0$ contribution is about 75%. (Actually this fraction decreases smoothly from about 80% near $E_x=15$ MeV to only about 50% near 26 MeV.) At wider angles most of the residual continuum is due to the strong $\Delta l=1$ collective resonance observed near $E_x=25$ MeV. Because of the dominance of the spin-transfer, isospin-transfer term over the isospin-transfer only term in the nucleon-nucleon effective interaction near 135 MeV, this analysis indicates that there must exist a considerable amount of 1^+ strength in the continuum above the GTGR, from 15 to about 30 MeV. If we ascribe *all* of the $\Delta l=0$ strength obtained from the multipole decomposition of this QSF-subtracted continuum to 1^+ (GT) strength, we obtain approximately 12 mb/sr in the 0° spectrum. This corresponds to about 25% of the 1^+ strength observed in the GTGR peaks. Because this strength is at a higher excitation energy than the 0^+, IAS, we must correct for the difference in momentum transfers, as discussed previously. Both the raw and "corrected" 1^+ strengths for this region are listed in Table I.

In order to consider also the possibility that much of the background subtracted for the 4—15 MeV complex also is 1^+, GT strength, we performed a similar multipole decomposition of this background. Figure 7 shows the angular distribution of the subtracted background. In a manner similar to that described above for the continuum angular distributions, we fit this angular distribution with a combination of $\Delta l=0$, 1, and 2 angular distributions. The overall fit is seen to be reasonably good and indicates that about 75% of the background subtracted at 0° must be assigned to the $\Delta l=0$ contribution. If we ascribe all of this $\Delta l=0$ strength to 1^+ (GT) strength, then we obtain an additional ~ 13 mb/sr in the 0° spectrum. Note that this result is in good agreement with the separate analysis of Osterfeld.[10] Both the raw and momentum-transfer corrected 1^+ strength from this region are listed in Table I.

From Table I we see that if we consider only the "peak" cross sections (viz., for the 2.52 MeV state, the 4.5—14.5 MeV GTGR, and the 16.8 MeV state), then we have a total 1^+ cross section of about 51 mb/sr, which is 43% of the simple GT sum-rule strength relative to the Fermi strength seen in the 0^+, IAS. If we consider also the (presumably) 1^+ strength seen in the background (under the 4—15 MeV complex) and in the continuum, the total 1^+ strength observed increases to about 82 mb/sr, or 69% of the simple sum-rule strength.

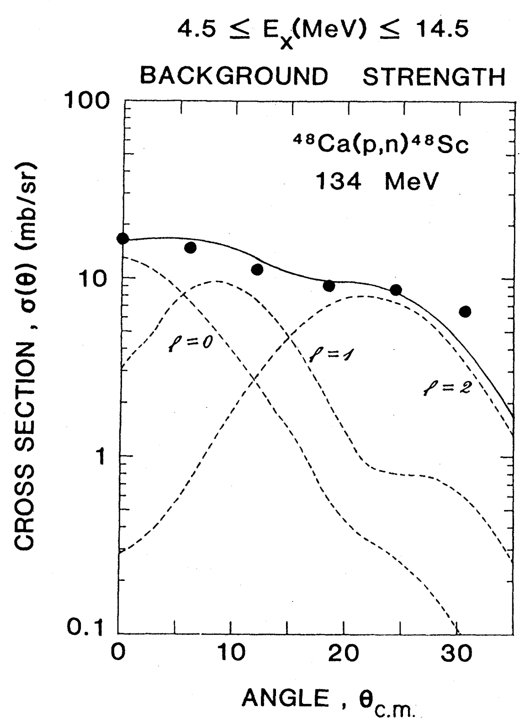

FIG. 7. Experimental angular distribution for the background under the GTGR region in the $^{48}Ca(p,n)^{48}Sc$ reaction at 134 MeV. The curves represent DWIA calculations for $\Delta l=0$, 1, and 2 transitions and were normalized to provide the best overall fit to the experimental angular distribution. See the text for further details.

Obviously, there are several areas open to interpretation in this analysis to obtain an estimate of the total 1^+, GT strength. First of all, the normalization of the QFS calculations to account completely for the continuum near $T_n=95$ MeV in the $^{40}Ca(p,n)$ reaction ignores any possible reaction strength to states in ^{40}Sc, including 1^+ states, in the continuum. Although the QFS calculation does appear to describe well the continuum and background for the $^{40}Ca(p,n)$ spectrum, this calculation certainly overestimates the QFS contributions. Since the normalization for the QFS background in the $^{48}Ca(p,n)$ spectrum is taken from the ^{40}Ca QFS normalization, the QFS subtraction for ^{48}Ca is likely too large as well. Thus, the residual spectrum is probably somewhat too small so that the 1^+ strength extracted this way probably represents a *lower limit.* Clearly the multipole decompositions introduce uncertainty in the final result as well, since the calculated angular distributions are model dependent. The actual shape of the various multipole angular distributions depends on both the J^π and the specific shell-model orbitals assumed for the final states. The shapes adopted here for the $\Delta l=1$ and 2 multipoles represent "average" shapes of several different calculations. Clearly, the amount of $\Delta l=0$ required to fit the continuum angular distributions is most sensitive to the $\Delta l=1$ shape near 0°. The results obtained here could be increased or decreased by *at least* 30% by a different (and possible) choice for the $\Delta l=1$ angular distribution shape. We note, in this regard, that the angular distribution of the ~ 1 MeV wide continuum observed between the GTGR and the $T=4$, 1^+ state at $E_x=16.8$ MeV is actually *peaked* at 0°. Since none of the $\Delta l=1$ calculated angular distributions provide a peaking at 0°, we conclude that there definitely is *some* $\Delta l=0$ strength in the continuum above the GTGR.

If we accept that this analysis provides a reasonable (or at least possible) estimate of the 1^+, GT strength in the $^{48}Ca(p,n)^{48}Sc$ reaction, we have the result that we can account for about 70% of the (minimum) simple sum-rule strength. We note that this fraction is similar to the fraction observed in the (p,n) reaction on light targets, viz., in the $^{14}C(p,n)^{14}N$ reaction,[39] the $^{18}O(P,n)^{18}F$ reaction,[40] and the $^{26}Mg(p,n)^{26}Al$ reaction.[41,42] In fact, in the (p,n) reaction on medium- and heavy-mass nuclei, it may be that typically about 50% of the *observed* GT strength is moved into the continuum (including the background under the GTGR), as estimated here for the $^{48}Ca(p,n)^{48}Sc$ reaction. This 1^+, GT strength in the continuum is apparently due primarily to ground-state correlations, as explained, for example, by Bertsch and Hamamoto[11] for $^{90}Zr(p,n)^{90}Nb$.

Finally, let us now consider the decision to subtract the QFS contributions to the nuclear continuum in order to determine only the 1^+ (GT) strength in the $^{48}Ca(p,n)^{48}Sc$ reaction. Certainly, this is not entirely valid. First of all, states in ^{48}Sc become unbound to proton emission at $E_x=9$ MeV, so that most of the continuum excited in the (p,n) reaction will rapidly proton decay. At some point, it becomes quantum-mechanically impossible to separate the (p,pn) QFS reaction from the (p,n) + proton emission process; it is important to realize, however, that the nuclear "spin filter" for isolating GT strength is lost in the QFS process. Since we are detecting neutrons, we know that the QFS must be (p,pn). Thus, the incident proton must be interacting with a neutron in the target. The QFS process can be described, for example, in a plane-wave impulse approximation by

$$\frac{d^2\sigma}{d\Omega\, dE} \propto \int \left[\frac{d\sigma}{d\Omega}\right]_{\rm pn} |\Phi_\alpha(q)|^2 d\phi ,$$

where $(d\sigma/d\Omega)$ is the cross section for free proton-neutron scattering and $|\Phi_\alpha(q)|^2$ is the Fourier transform of the single-particle wave function for the struck neutron.[33] This is the model we adopted for describing the QFS and, as discussed above, it provides a reasonable description of the continua in the ^{40}Ca and ^{48}Ca(p,nx) reactions (with the same normalization factors). In earlier work,[32] we showed that such calculations also provide a reasonable description of the ratio between (p,px) and (p,nx) continua and concluded that QFS probably dominates the high-energy portion of the forward-angle continua in such spectra at medium energies ($\gtrsim 100$ MeV). The free proton-neutron scattering cross section involves the isoscalar terms of the N-N interaction as well as the isovector terms. Because all of the central terms in the N-N effective interaction can contribute to QFS at 0°, we have the result that all of the $\Delta l=0$ component of the QFS will *not* correspond to GT strength. Of course, it is not really possible to separate the QFS from the (p,n) + proton decay process; but in order to obtain a first estimate of the GT strength, we started by simply subtracting the calculated QFS strength, normalized in the ^{40}Ca(p,nx) reaction, and performing a multipole decomposition of the residual continuum, as described above.

The amount of GT strength involved in QFS is difficult to estimate. The free proton-neutron scattering cross section involves the isoscalar terms of the N-N interaction as well as the isovector terms. In a single-scattering process, there are two ways to produce a neutron at 0° via a (p,pn) quasifree scattering reaction. In the first way, the incident proton charge exchanges with one of the target neutrons and is scattered forward at 0° with small momentum transfer. This process is necessarily mediated by the isovector terms (such as $V_{\sigma\tau}$ and V_τ). The second way involves a "knockon" collision between the incident proton and a target neutron such that the neutron is ejected at 0°. This latter process can involve the isoscalar terms, such as V_0 and V_σ, and occurs with large momentum transfer. To estimate properly the relative contribution of $V_{\sigma\tau}$ to the total strength of the effective interaction, it is necessary to compare strengths of the isovector terms at low momentum transfer with strengths of isoscalar terms at large momentum transfer. A proton with incident energy of 134 MeV has a momentum of 2.63 fm^{-1}. A neutron emerging with 30 MeV less energy has a momentum of 2.25 fm^{-1}. Thus, the charge-exchange process occurs at a momentum transfer of about 0.4 fm^{-1} at 0°. The neutron knockout process occurs at a momentum transfer of about 2.25 fm^{-1} (ignoring the Fermi motion of the struck neutron). From the momentum-transfer dependence of the 140 MeV N-N effective interaction presented by Love, Franey, and Petrovich,[44] we obtain a rough estimate of the fraction of the total strength which would be in the $V_{\sigma\tau}$ term. Taking the isovector terms at 0.4 fm^{-1} and the isoscalar terms at 2.25 fm^{-1}, and ignoring interference effects between terms, we find that the GT strength is roughly one-third of the total QFS at 0°. The total ^{40}Ca(p,pn) QFS cross section at 0° is ~200 mb/sr, which is obtained by integrating the normalized QFS calculation shown in Fig. 5 over all emitted neutron energies (viz., down to $T_{\rm n}=0$ MeV). One-third of this total is ~67 mb/sr, which, if added to the total GT cross section of Table I, would more than satisfy the simple GT sum rule.

An alternative method to our above analysis of the continuum above the GTGR would be simply to perform a multipole decomposition of the total continuum, without first subtracting a QFS contribution. We present such a decomposition in Fig. 8. The experimental points are the total continuum from just above the GTGR up to the highest excitation energy available in these measurements. The continuum was corrected for cosmic ray and "wrap-around" backgrounds as discussed earlier. Shown are the same $\Delta l=0$, 1, and 2 angular distributions used to fit the residual background described above. The normalization of the angular distributions were determined to provide

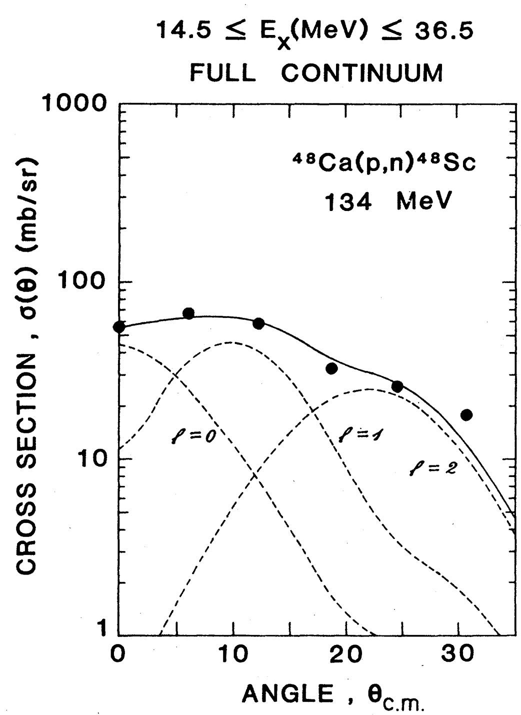

FIG. 8. Experimental angular distribution for the full continuum region with excitation energies between $14.5 \le E_x({\rm MeV}) \le 36.5$ for the ^{48}Ca(p,n)^{48}Sc reaction. The curves represent DWIA calculations for $\Delta l=0$, 1, and 2 transitions and were normalized to provide the best overall fit to the experimental angular distribution. See the text for further details.

the best fit to the experimental angular distribution from 0° to beyond 20°. The result is that $\sim 80\%$ of the 0° cross section (or 44 mb/sr) is ascribed to $\Delta l = 0$ contributions. (Note that an analysis which divides the continuum up into ~ 4 MeV bins yields the same result for the total $\Delta l = 0$ cross section at 0°.) Now one must attempt to estimate what fraction of *this* 44 mb/sr cross section is due to the $V_{\sigma\tau}$ term of the N-N effective interaction, in order to estimate GT strength. If one accepts that the continuum is dominated by QFS (at least as a doorway mechanism), and that the $\Delta l = 0$ contributions are dominated by the central terms of the N-N effective interaction, then we are interested in the fraction of the central part of the N-N interaction that is due to the $V_{\sigma\tau}$ term. Using the momentum-transfer dependence indicated by Love, Franey, and Petrovich[44] again, and considering the isovector terms ($V_{\sigma\tau}$ and V_{τ}) at 0.4 fm^{-1} and the isoscalar terms (V_0 and V_{σ}) at 2.25 fm^{-1}, one obtains an estimate that the $V_{\sigma\tau}$ term would account for $\sim 67\%$ of the total central strength. (Note that this fraction is larger here than in the analysis of the QFS contribution to the 0° spectrum because here we are considering only the $\Delta l = 0$ part of a multipole decomposition.) Thus, we estimate from this analysis that the total GT strength in the continuum from 14.5 to 36.5 MeV is ~ 29 mb/sr, or ~ 42 mb/sr when corrected to be at the same momentum transfer as the 0^+, IAS transition. If this amount is used in Table I in place of the 17 mb/sr indicated for the continuum, a total GT-corrected cross section of 107 mb/sr is obtained. This value would correspond to 90% of the amount required to satisfy the simple sum rule.

It is important to realize that all of these estimates for GT strength in the continuum are ambiguous. Although it is well known that the IAS transition carries essentially all of the Fermi strength observed in beta decay, there are some questions relating to the QFS process. If the $V_{\sigma\tau}$ contribution from QFS is to be included in the total GT strength, then it is not clear whether or not the strength associated with the V_{τ} term should be included in the total Fermi strength; moreover, attempts to determine what fraction of the QFS contribution might be GT strength by comparing the relative strengths of the various terms in the N-N effective interaction are risky. Certainly a more sophisticated theoretical analysis is warranted.

V. SUMMARY

Because of the dominance of the spin-transfer, isospin-transfer term in the nucleon-nucleon effective interaction at low-momentum transfers, the $^{48}Ca(p,n)^{48}Sc$ spectrum at 0° is dominated by 1^+ excitations. This 1^+, or Gamow-Teller, strength is separated into distinct groups. First, we see a strong excitation of the $T = 3$, 1^+ state at 2.52 MeV, which is part of the $(f_{7/2}, f_{7/2}^{-1})$ band of states. Then we see a strongly-excited complex of strength between 4.5 and 14.5 MeV of excitation which is the Gamow-Teller giant resonance (GTGR) for this reaction. Finally, we see a single $T = 4$, 1^+ state about 2 MeV above the GTGR, in good agreement with a shell-model prediction. If we sum all of the 1^+ strength observed in these three regions, using simple fitted backgrounds, we find about 48% of the expected strength compared to DWIA calculations with reasonable shell-model wave functions. If we believe that the observed 1^+ strength should satisfy the simple sum rule for GT strength in this reaction, we find that the summed strength represents 43% of such a sum rule, taken relative to the Fermi strength assumed to be concentrated in the 0^+, IAS. These fractions of the expected 1^+, GT strength are similar to those observed in other medium- and heavy-mass nuclei.

Following indications from various recent theoretical calculations, we considered the possibility that some of the missing GT strength might be in the background subtracted underneath the GTGR or in the continuum above the GTGR. In order to identify 1^+ strength in ^{48}Sc, we began by subtracting quasifree scattering (QFS) contributions from the continuum using PWIA calculations, normalized to the continuum in ^{40}Ca. (These backgrounds are very similar to those obtained in a microscopic calculation for this reaction.) We then performed a multipole analysis of the residual continuum in order to extract the $\Delta l = 0$ contributions. A similar multipole analysis was performed for the background subtracted under the GTGR (from 4.5 to 14.5 MeV). If we accept the total $\Delta l = 0$ strength obtained in these analyses as additional 1^+, GT strength, we find that the total strength becomes approximately 70% of the sum rule, similar to the fraction observed in light nuclei and deduced by other workers performing similar analyses, on medium-mass nuclei. If one considers also possible Gamow-Teller strength proceeding into the QFS continuum, then the simple sum rule may be satisfied. Alternatively, if we perform a multipole decomposition of the entire continuum from just above the GTGR up to the highest excitation energy available in these measurements (viz., 36.5 MeV), we find that the estimated GT strength would total about 90% of the simple sum rule. Certainly the uncertainties in all these methods is large. Furthermore, we note that the effects of the V_{τ} (Fermi) contributions in QFS are unclear.

In conclusion, the complex analysis required to extract the total Gamow-Teller strength for this reaction indicates that configuration mixing, ground-state correlations, and QFS contributions all combine to make this a difficult situation for quantitative analysis. The results obtained here are expected to be similar for other medium- and heavy-mass nuclei. The "experimental" evidence for missing GT strength in the (p,n) reaction on medium- and heavy-mass nuclei is seen to depend strongly on the reaction mechanisms assumed to excite the relatively large continuum.

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