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Gamow-Teller strength in the $^{54}Fe(p,n)^{54}Co$ reaction at 135 MeV

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The $^{54}Fe(p,n)^{54}Co$ reaction was studied at 135 MeV by the time-of-flight technique. Neutrons were detected with an energy resolution of 245 keV in large-volume, mean-timed counters at a flight path of 125 m. The forward-angle spectra are dominated by the excitation of 1^+ states with characteristic $\Delta l=0$ angular distributions peaked at 0°. The strengths of the 1^+ excitations are interpreted as being equivalent to Gamow-Teller (GT) strengths excited in beta decay. This strength is observed to be highly fragmented; GT strength is identified in more than 30 states. The $B(\mathrm{GT}-)$ strength is obtained relative to the Fermi strength $B(\mathrm{F})$ assumed to be concentrated in the 0^+, isobaric-analog ground state. The total $B(\mathrm{GT}-)$ strength observed in discrete states, combined with the $B(\mathrm{GT}+)$ strength obtained from the (n,p) reaction, yields a lower limit of 48 percent of the $3(N-Z)$ sum rule. Inclusion of $\Delta l=0$ strength in the background and continuum above a quasifree scattering background increases this lower limit to 73 percent. If one considers the $\Delta l=0$ strength observed in the full background and continuum up to $E_x=25$ MeV, the entire sum rule may be satisfied. The observed distribution of GT strength is in good agreement with a truncated $1f$-$2p$ shell-model calculation.

I. INTRODUCTION

The quenching of Gamow-Teller (GT) strength in nuclei is a topic of high current interest. This quenching was first observed in beta decay,[1] but has been studied extensively with the (p,n) reaction at medium energies.[2–5] Insofar as the (p,n) reaction proceeds predominantly via one-step processes, transitions to 1^+ states from even-even nuclei proceed via the isovector spin-transfer term of the nucleon-nucleon effective interaction. At low-momentum transfer, the strengths of these transitions are similar to those of GT beta decays. The usefulness of (p,n) studies of GT strength lies in the fact that the (p,n) reaction is not limited by Q-value restrictions and can excite the entire profile of GT strength. Thus the (p,n) reaction provides a more complete sampling of the distribution of GT strength.

The quenching of GT strength observed in (p,n) reactions is usually deduced by comparison with the simple, model-independent, sum rule[6]

$$S_{\beta^-}-S_{\beta^+}=3(N-Z)\ . \tag{1}$$

Experimental (p,n) and (n,p) measurements at intermediate energies and low-momentum transfer yield a measure of the GT strength which we denote as $B(\mathrm{GT}-)$ and $B(\mathrm{GT}+)$. If, in these experiments, one could locate GT strength over the entire energy domain, the sum of the empirical strengths [i.e., the $B(\mathrm{GT})$'s] should correspond to S_{β^-} and S_{β^+}, respectively. Many (p,n) measurements have been performed to measure $B(\mathrm{GT}-)$. Usually, $B(\mathrm{GT}+)$ is assumed to be small and is neglected; in general, this assumption is not correct. $B(\mathrm{GT}+)$ can be measured directly with the (n,p) reaction; such measurements have been done for a few cases at medium energies with the charge-exchange facility at TRIUMF. One of the targets studied was ^{54}Fe; Vetterli *et al.*[7] reported a measurement of $\sum_0^{\sim 10\ \mathrm{MeV}}B(\mathrm{GT}+)=3.1\pm0.6$ from the $^{54}Fe(n,p)$ reaction at 298 MeV. This result can be combined with the earlier determination of $\sum_0^{\sim 40\ \mathrm{MeV}}B(\mathrm{GT}-)=7.8\pm1.9$ from the study of the $^{54}Fe(p,n)$ reaction at 160 MeV by Rapaport *et al.*[8] to yield

$$\sum_0^{\sim 40\ \mathrm{MeV}}B(\mathrm{GT}-)-\sum_0^{\sim 10\ \mathrm{MeV}}B(\mathrm{GT}+)=7.8-3.1$$
$$=4.7\pm2.0\ .$$

This result provides a lower limit which is three-fourths ($\pm$ one-third) of the $3(N-Z)=6$ sum rule.

It is significant to note that the large uncertainty in this result prevents one from making any real conclusion about the amount of quenching in this reaction. Somewhat surprisingly, this large uncertainty comes from the (p,n) measurements, and not from the (n,p) experiment. Clearly, what is needed is to reduce the uncertainty on the (p,n) determination of $B(\mathrm{GT}-)$. This paper reports the analysis of new (p,n) measurements on ^{54}Fe at 135 MeV with significantly better energy resolution than the earlier measurements. The measurements reported here have an energy resolution of 245 keV and provide a clean separation of the 0^+, isobaric-analog ground state (IAS) from the large 1^+, GT state at 0.94 MeV, as well as better resolution in the Gamow-Teller giant resonance (GTGR). The former is important because the GT strength is obtained relative to the Fermi strength assumed to be concentrated in the 0^+ IAS. This state was not resolved clearly in the earlier experiment and had to be extracted by peak fitting. The better resolution in the GTGR is important in order to be able to separate possible non $\Delta l=0$ components more unambiguously. In this experiment, we see the GTGR to be fragmented into at least 30 states. It is desirable to obtain separate angular distributions for as many of these states as possible in order to obtain a more accurate determination of the GT strength.

From the analysis of this experiment, we are able to determine the amount of GT strength in the discrete peaks accurately enough that the uncertainty in $B(\mathrm{GT}-)$ from this source is less than reported for $B(\mathrm{GT}+)$ from the (n,p) reaction; however, as discussed by many workers, it is necessary to consider also possible GT strength in the background underneath the observed peaks in the GTGR and in the continuum above the GTGR. The determination of these contributions to the total GT strength is much more uncertain. We consider such contributions in this reaction in two ways. First, we subtract a calculated quasifree scattering (QFS) background to obtain "residual" (p,n) spectra. QFS is known to be important in medium-energy reactions, and although it may carry GT strength, it will no longer be revealed as $\Delta l=0$ strength (because it involves three bodies in the final state). While it is certainly true that the (p,n) reaction to an unbound state becomes quantum mechanically indistinguishable from the (p,pn) reaction (i.e., QFS), we feel that it is important to recognize that much of the continuum is due to QFS and will not reveal GT strength in the usual way. A multipole decomposition was performed of the "residual" background in order to obtain the $\Delta l=0$ contribution, which is then interpreted as GT strength. We regard the subtraction of the QFS background as a first-order correction that will result in an underestimation of the background GT strength. Finally, we performed a multipole decomposition of the full background and continuum up to 25 MeV, again taking the $\Delta l=0$ contribution as GT strength. Because this analysis clearly includes QFS strength, it provides an overestimate of the GT strength in this region.

The experimental procedure, data reduction, and the GT strength analyses are described below. It is shown that the GT strength in the discrete peaks can be extracted accurately, but that the amount of GT strength in the background and continuum remains highly uncertain.

II. EXPERIMENTAL PROCEDURE

The experiment was performed at the Indiana University Cyclotron Facility with the beam-swinger system.[9] The basic experimental arrangement and data-reduction procedures were similar to those described previously.[4,5]

Neutron kinetic energies were measured by the time-of-flight (TOF) technique. A beam of 135 MeV protons was obtained from the cyclotron in narrow beam bursts with a duration of typically 350 ps. Neutrons were detected in three detector stations at 0°, 24°, and 45° with respect to the undeflected proton beam. The flight paths were 125.2, 133.6, and 80.9 m, respectively. For the work reported here, only measurements from the 0° and 24° stations were considered. The neutron detectors were rectangular bars of fast plastic scintillator 10.2 cm thick. Three separate detectors each 1.02 m long by 0.51 m high were combined for a total frontal area of 1.55 m^2 in the 0° station. Two detectors were used in the 24° station, one was 1.02 m long by 1.02 m high and the other was 1.02 m long by 0.51 m high, for a combined frontal area of 1.55 m^2. Each neutron detector has tapered plexiglass light pipes attached on the two ends and coupled to 12.7 cm diam. phototubes. Timing signals were derived from each end and combined in a mean-timer circuit[10] to provide the timing signal from each detector. Overall time resolutions of about 800 ps were obtained, including contributions from the beam burst width (≈ 350 ps) and the beam energy spread (≈ 400 ps), energy loss in the target (≈ 450 ps), neutron transit times in the detectors (≈ 530 ps), and the intrinsic time dispersions of each detector (≈ 300 ps). (Note that these contributions are not all Gaussian and do not combine simply in quadrature. See Ref. 4.) This overall time resolution provided an energy resolution of about 245 keV. The large-volume neutron detectors were described in more detail previously.[11] The ^{54}Fe target was a 37.6 ± 1.9 mg/cm^2 self-supporting foil.

III. DATA REDUCTION

During the experimental run, neutron time-of-flight (TOF) spectra were recorded simultaneously at various pulse-height thresholds between 30 and 70 MeV equivalent-electron energy (MeVee). For a final analysis, a threshold of 55 MeVee was chosen as the best compromise between higher thresholds that reduce overlap of slow neutrons from the previous beam burst and lower thresholds that provide increased counting statistics. We obtained excitation-energy spectra from the measured TOF spectra by using the known flight path and a calibration of the time-to-amplitude converter. The known Q-value of the ^{54}Fe$(p,n)^{54}$Co(g.s.) reaction served as a calibration point for determining absolute neutron energies. The excitation-energy spectrum at 0.2° is shown in Fig. 1.

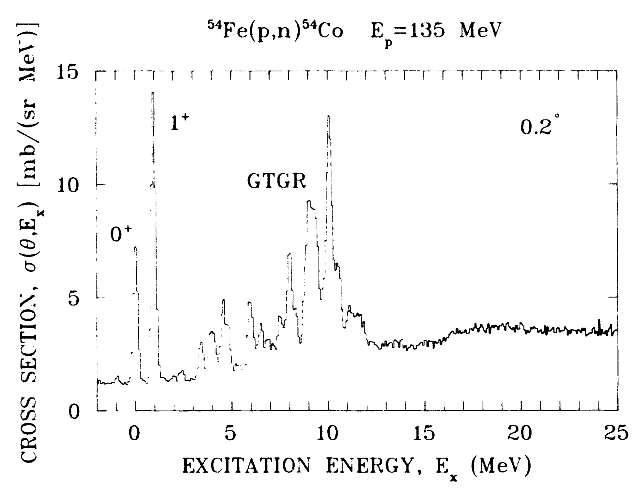

FIG. 1. Experimental ^{54}Fe$(p,n)^{54}$Co excitation-energy spectrum at 135 MeV and 0.2°.

Yields for transitions in the ^{54}Fe(p,n)^{54}Co reaction were obtained by peak fitting of the TOF spectra, as described below. Cross sections were obtained by combining the yields with the measured geometrical parameters, the beam integration, and the measured target thickness. The neutron detector efficiencies were obtained from a Monte Carlo computer code[12] which has been tested extensively at these energies.[13,14] The overall absolute cross sections so obtained were checked by remeasuring the known ^{12}C(p,n)^{12}N(g.s.) reaction.[13] The experimental procedure and data reduction are similar to that described in more detail in Ref. 4. The uncertainty in the overall scale factor is dominated by the uncertainty in the detector efficiencies and is estimated to be $\pm 12\%$. The Gamow-Teller strength was extracted from the observed peaks and from the background and continuum as discussed below.

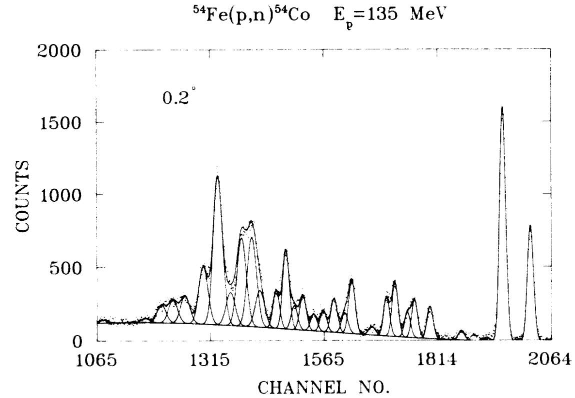

FIG. 2. Fit to the ^{54}Fe(p,n)^{54}Co, time-of-flight spectrum at 0.2°.

IV. GAMOW-TELLER STRENGTH IN DISCRETE PEAKS

Gamow-Teller strength in the peaks observed in the 0° spectrum (see Fig. 1) was considered first. As discussed here, this strength was extracted in a relatively unambiguous way, with a small uncertainty.

Cosmic-ray background and "wraparound" of low-energy neutrons from previous beam bursts were subtracted for each TOF spectrum, in a manner similar to that described previously.[4] We used an improved version of the peak-fitting code of Bevington[15] to fit the spectra at 0°, 5°, 11°, 17°, and 24° simultaneously with up to 31 Gaussian peaks on a cubic polynomial background. The minimum number of peaks was used in order to obtain good fits at each angle, and care was taken to ensure that the fits changed smoothly from angle to angle. In general, fewer peaks were observed at the wider angles; many of the small peaks observed at 0° disappeared into the background away from 0°. The widths of the peaks were constrained to be the same in three groups. The widths were observed to become broader with increasing excitation energy, presumably because of increased spreading and decay widths. The fits were judged to be good, with small reduced chi squares. The fit to the 0° spectrum is shown in Fig. 2.

The extracted $\Delta l=0$ cross sections at 0°, associated with peaks in the entire 0–12 MeV range of excitation energy, are listed in Table I. The Gamow-Teller giant resonance (GTGR) is seen to be highly fragmented; 30 peaks are observed in the 0° spectrum which contain $\Delta l=0$ strength. The ground state (IAS), 0^+ transition is seen clearly and is separated well from the known 1^+ state at 0.94 MeV. A number of smaller states with predominantly $\Delta l=0$ angular distributions are seen between about 3 and 8 MeV, as well as a large doublet near 9 MeV, and the largest single transition at 10.1 MeV. A small amount of $\Delta l=0$ strength is then observed up to about 13 MeV where individual states can no longer be recognized above the continuum. The majority of the strength observed in the 0° spectrum is $\Delta l=0$ strength, which we interpret here as GT strength. Sixteen of the 30 peaks containing $\Delta l=0$ strength appear to be pure $\Delta l=0$ transitions and they contain 86% of the total $\Delta l=0$ strength. 14 of the peaks appear to be mixtures of more than one multipole; but they are relatively weak transitions. The angular distributions for the transitions to the 0^+, IAS and to the two largest 1^+ states at $E_x=0.94$ and 10.06 MeV, are shown in Figs. 3–5. The experimental angular distributions are compared with DWIA calculations as described below, using shell-model wavefunctions from the $1f$-$2p$ calculation described in Sec. VI.

The amount of $\Delta l=0$ strength in each state was determined from an analysis of the extracted angular distribution for each peak. For the transitions judged to be pure $\Delta l=0$, the strength is taken simply as the cross section observed at 0°. For the mixed transitions, $\Delta l=1$ and/or $\Delta l=2$ shapes were subtracted to obtain the $\Delta l=0$ contributions at 0°. These shapes are discussed below. The uncertainties presented in Table I are relative uncertainties only. For those peaks that appear to be pure $\Delta l=0$ transitions, the uncertainties are taken from the error matrix of the fitting code. For the mixed transitions, we estimate the uncertainty in the amount of $\Delta l=0$ strength at 0° to be $\pm 30\%$. Because the amount of $\Delta l=0$ strength in mixed transitions is only about 14% of the total, this uncertainty introduces an uncertainty in the total $\Delta l=0$ strength of about $\pm 2\%$. The net uncertainty in the total amount of $\Delta l=0$ strength is $\pm 3\%$. These uncertainties are relative only. The absolute uncertainty is dominated by the overall scale uncertainty in the cross sections and is $\pm 12\%$ as discussed above.

The amount of GT strength associated with the observed $\Delta l=0$ strength is obtained relative to the Fermi strength assumed to be concentrated in the 0^+, IAS (the ground state of ^{54}Co). This conversion is performed in a manner similar to that described earlier for the analysis of GT strength observed in the ^{48}Ca(p,n)^{48}Sc at 135 MeV.[4] Basically, one assumes that the "expected" ratio between GT and Fermi strength is given by the ratio of the simple sum rules, times the ratio of the GT and Fermi matrix elements in the nucleon-nucleon (N-N) effective interaction. The first ratio is just $3(N-Z)/(N-Z)=3$. The second ratio, including a ratio of the distortion factors for GT and Fermi transitions, was determined

TABLE I. Experimental ^{54}Fe$(p,n)^{54}$Co(1^+) cross sections and B(GT) values at 135 MeV in discrete peaks. m is mixed transition (see text).

E_x [MeV]	$\sigma_{GT}(0.2°)$ [mb/sr]	$\sigma_{GT}(@q=q_{IAS})$ [mb/sr]	B_{pn}(GT)
0.00(0$^+$,IAS)	1.52 (0.02)[a]	1.52	$B(F)=2$
0.94	3.20 (0.02)	3.23	0.736
2.01	0.01 (0.004)m	0.01	0.002
2.35	0.05 (0.02)m	0.06	0.013
3.39	0.38 (0.13)m	0.40	0.090
3.90	0.51 (0.02)	0.53	0.121
4.13	0.31 (0.10)m	0.33	0.074
4.53	0.77 (0.02)	0.81	0.185
4.80	0.54 (0.02)	0.58	0.133
5.20	0.04 (0.01)m	0.04	0.009
5.40	0.02 (0.01)m	0.03	0.006
5.92	0.82 (0.11)	0.90	0.206
6.15	0.30 (0.10)m	0.33	0.075
6.48	0.48 (0.16)m	0.54	0.122
6.82	0.33 (0.11)m	0.37	0.083
7.12	0.26 (0.08)m	0.29	0.066
7.46	0.54 (0.18)m	0.62	0.140
7.73	0.35 (0.12)m	0.40	0.090
7.99	1.25 (0.03)	1.44	0.329
8.29	0.60 (0.04)	0.70	0.159
8.79	0.83 (0.05)	0.98	0.222
9.03	2.03 (0.05)	2.42	0.550
9.34	2.01 (0.04)	2.25	0.513
9.68	0.75 (0.04)	0.91	0.207
10.06	3.42 (0.14)	4.20	0.956
10.50	1.33 (0.08)	1.65	0.376
11.05	0.64 (0.05)	0.81	0.184
11.40	0.53 (0.05)	0.68	0.155
11.75	0.41 (0.02)	0.54	0.122
12.21	0.05 (0.02)m	0.07	0.015
13.44	0.04 (0.01)m	0.05	0.012
	$\Sigma(1^+)=22.71$ (0.68)[b]		$\Sigma=5.951$ (0.208)[b]

[a]Individual uncertainties are relative only (see text).
[b]Net statistical uncertainty is relative to Fermi strength in 0^+, IAS. Full uncertainty $=\pm0.4$, see text.

empirically from the ^{14}C(p,n) reaction by Taddeucci *et al.*[3] to be 6.0 ± 0.1 (at 135 MeV). The net result, including a small correction for the ratio of the incoming and outgoing wave numbers (see Ref. 4) is that the "expected" ratio of GT to Fermi strength in the (p,n) reaction is 17.4. Hence, to obtain GT strength, in B(GT) units where the value for the beta decay of the free neutron is 3, we use the expression,

$$B_{pn}(\mathrm{GT})=\frac{\sigma_{\mathrm{GT}}(E_x)}{\sigma_F(\mathrm{IAS})}\frac{1}{17.4}3(N-Z)\ . \tag{2}$$

In this expression, it is necessary that the GT cross sections be extrapolated to be at the same momentum transfer as the Fermi cross section, which for the ^{54}Fe$(p,n)^{54}$Co reaction is the ground-state transition. This extrapolation was performed with calculations from the distorted-wave impulse-approximation code DW81.[16] These calculations used the nucleon-nucleon effective interaction of Franey and Love at 140 MeV[17] and the global optical-model potentials of Schwandt *et al.*[18] Several calculations were performed for some of the large 1^+ states predicted by shell-model calculations[19] (see below), as a function of excitation energy in order to obtain a general curve which could be used to provide this extrapolation. Table I lists the experimental 1^+ cross sections at 0°, their observed excitation energies, the extrapolated cross section values, and the resulting B(GT) values obtained using Eq. (2).

The net result of this determination of GT strength in discrete peaks is, from Table I, $\sum_0^{14\,\mathrm{MeV}}B(\mathrm{GT}-)=6.0$. The statistical uncertainty, as presented in Table I is ±0.2. This uncertainty must be combined with an estimated uncertainty for the GT to IAS ratio method adopted here. Taddeucci *et al.* estimate this uncertainty to be $\pm6\%$.[3] They find that this uncertainty is consistent with that estimated for DWIA comparisons and for use of analog beta-decay strengths to determine B_{pn}(GT)

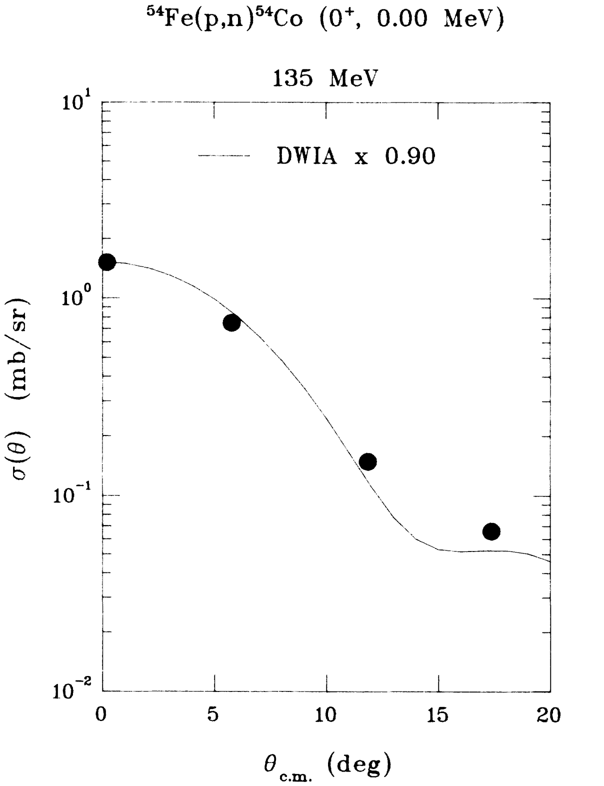

FIG. 3. Angular distribution for the $^{54}Fe(p,n)^{54}Co(0^+,0.00$ MeV) reaction at 135 MeV. The solid line represents a DWIA calculation with the normalization indicated (see text).

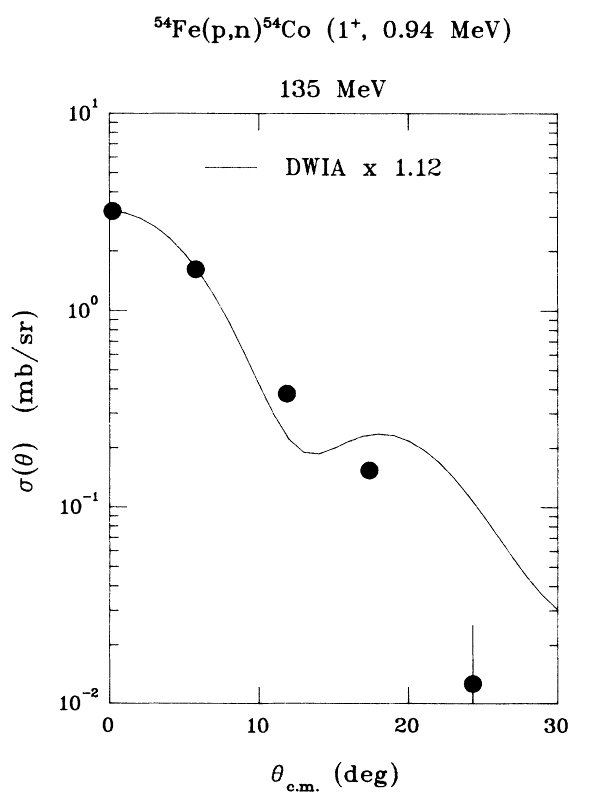

FIG. 4. Angular distribution for the $^{54}Fe(p,n)^{54}Co$ $+(1^+,0.94$ MeV) reaction at 135 MeV. The solid line represents a DWIA calculation with the normalization indicated (see text).

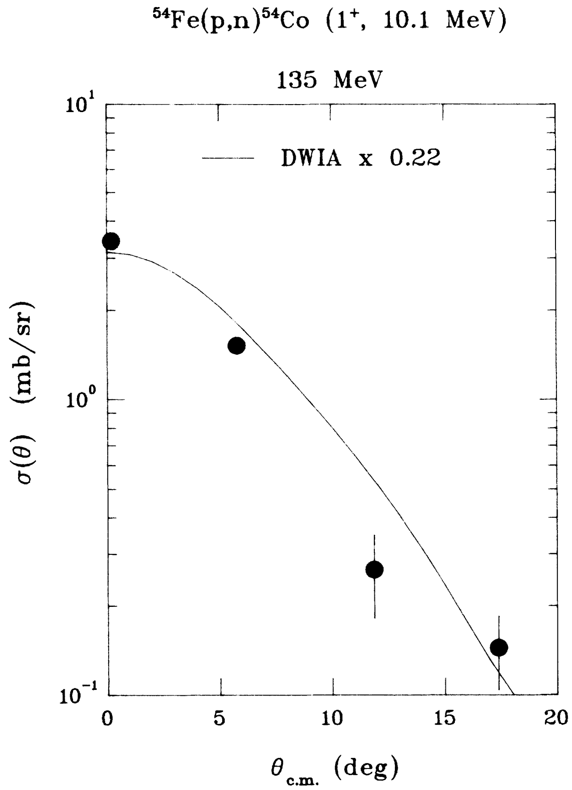

FIG. 5. Angular distribution for the $^{54}Fe(p,n)^{54}Co$ $(1^+,10.1$ MeV) reaction at 135 MeV. The solid line represents a DWIA calculation with the normalization indicated (see text).

values from (p,n) cross sections. Combining the statistical uncertainty together with this "systematic" uncertainty, we have the result that $\sum_0^{14\,\mathrm{MeV}} B(\mathrm{GT}-) = 6.0 \pm 0.4$, for the present work. This result can be combined with the value for $B(\mathrm{GT}+)$ from the (n,p) measurements (see above) to obtain a new lower limit compared to the sum rule

$$\sum_0^{14\,\mathrm{MeV}} B(\mathrm{GT}-) - \sum_0^{10\,\mathrm{MeV}} B(\mathrm{GT}+) = 6.0 - 3.1$$
$$= 2.9 \pm 0.7\ .$$

This value is only 48 $(\pm 12)\%$ of the simple sum rule value of 6. It is significant that the result presented here for $B(\mathrm{GT}-)$ has a small uncertainty (± 0.4); however, this is for GT strength in discrete peaks only. We now must consider GT strength in the background and continuum.

V. GAMOW-TELLER STRENGTH IN THE BACKGROUND AND CONTINUUM

The above analysis does not consider possible GT strength in the background underneath the GTGR or in the continuum above the GTGR. GT strength in these regions is possible via configuration mixing with states with complicated nuclear structures; for example, Osterfeld[20] estimated GT strength in the background and continuum in the $^{48}Ca(p,n)$ and $^{90}Zr(p,n)$ reactions. His

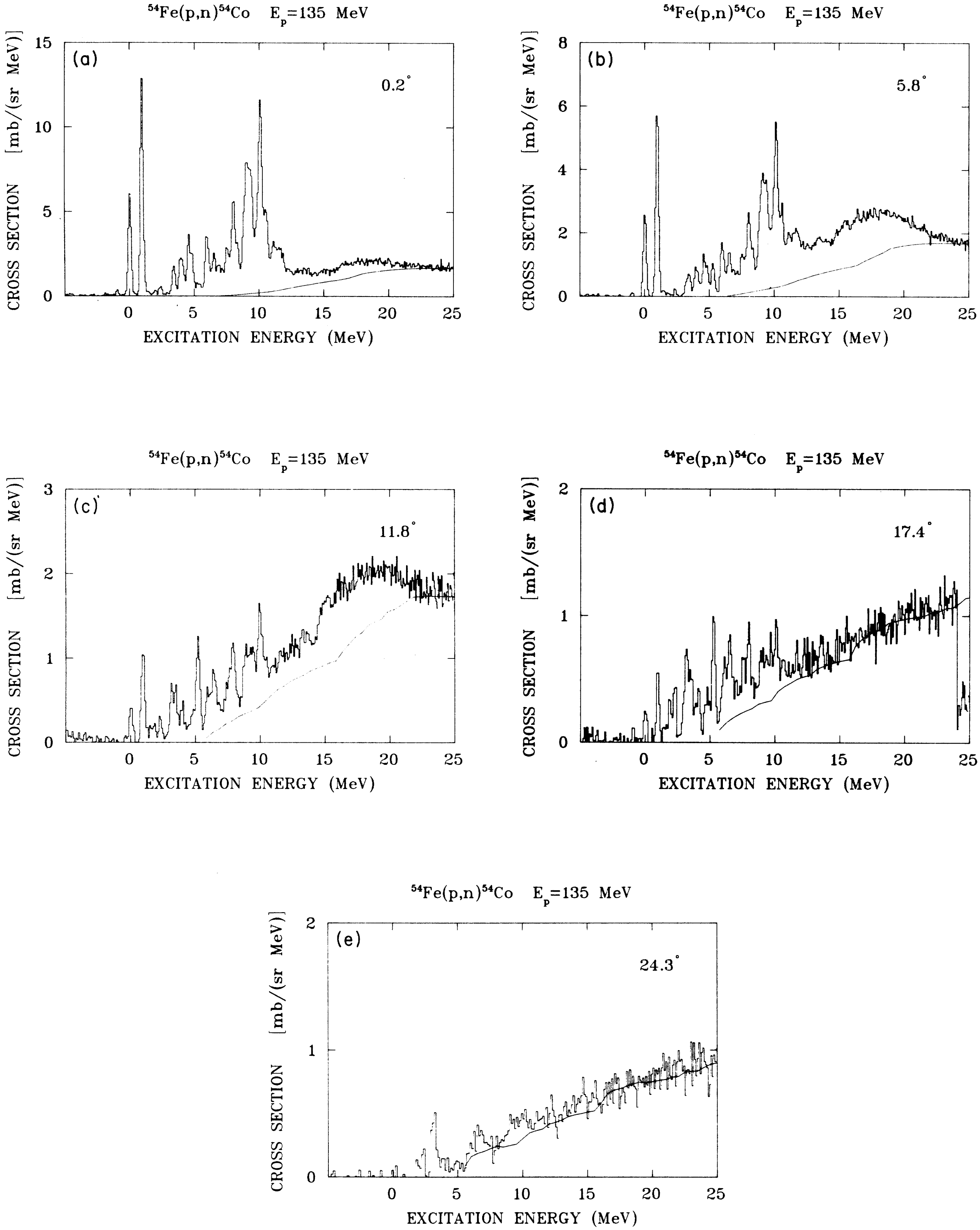

FIG. 6. Experimental excitation-energy spectra for the ^{54}Fe$(p,n)^{54}$Co reaction at 0.2°, 5.8°, 11.8°, 17.4°, and 24.3° and 135 MeV. The solid lines represent a PWIA quasifree scattering calculation (see text).

microscopic calculations considered transitions to bound and unbound final states of all possible spins that could be reached via particle-hole doorway states. His calculations reproduced the forward-angle spectra in these reactions very well and indicate that the majority of the background and much of the continuum is GT strength. Also, Bertsch and Hamamoto[21] reported that a perturbative calculation indicates that $2p$-$2h$ correlations in the target wave function will cause a significant amount [$\approx 30\%$ 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 such indications, we consider here possible GT strength in these regions. The analyses presented here are similar to those performed earlier for the ^{48}Ca(p,n)^{48}Sc reaction.[4]

A. GT strength in the QFS subtracted residual background

In a first analysis, we consider only possible GT strength above a calculated quasifree scattering (QFS) background. We start this way because QFS is known to be significant and will not reveal GT strength with a $\Delta l=0$ angular distribution signature because there are three bodies in the final state. In earlier work,[22] which compared (p,n) and (p,p') spectra from 90 MeV protons on several nuclei, it was shown that the high-energy portions of the forward-angle spectra were reproduced well by such QFS calculations. Also, as shown in Ref. 4, such calculations can reproduce the high-energy protons of the forward-angle spectra in both the ^{40}Ca(p,n) and ^{48}Ca(p,n) reactions at 135 MeV simultaneously (i.e., with the same normalization factor), even though the magnitudes of the continua are quite different. We use the same QFS calculations here to describe the continua in the forward-angle ^{54}Fe(p,n)^{54}Co spectra.

The QFS calculations were performed with the code developed by Wu[23] based on the formula obtained by Wolff.[24] 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 with binding energies obtained from neutron knockout measurements[25] and potentials obtained from Elton and Swift.[26] The QFS calculations were normalized to fit through the observed ^{54}Fe(p,n) continuum at $E_x=25$ MeV. Because these are plane-wave calculations, some normalization is expected. The normalization factor required is ≈ 0.2 and is about that expected for distortion.

The QFS calculations are shown in Fig. 6 at 0.2°, 5.8°, 11.8°, 17.4°, and 24.3° compared with the ^{54}Fe(p,n) excitation-energy spectra. The calculations describe the continua in a reasonable way. At forward angles, the GTGR (from 0 to 12 MeV) and the collective $\Delta l=1$ resonance (from 14 to 22 MeV) are observed clearly above the calculation. Note that the cutoff at $E_x=4.6$ MeV in the QFS calculations is determined from the known neutron separation energy in ^{54}Co. In the wide-

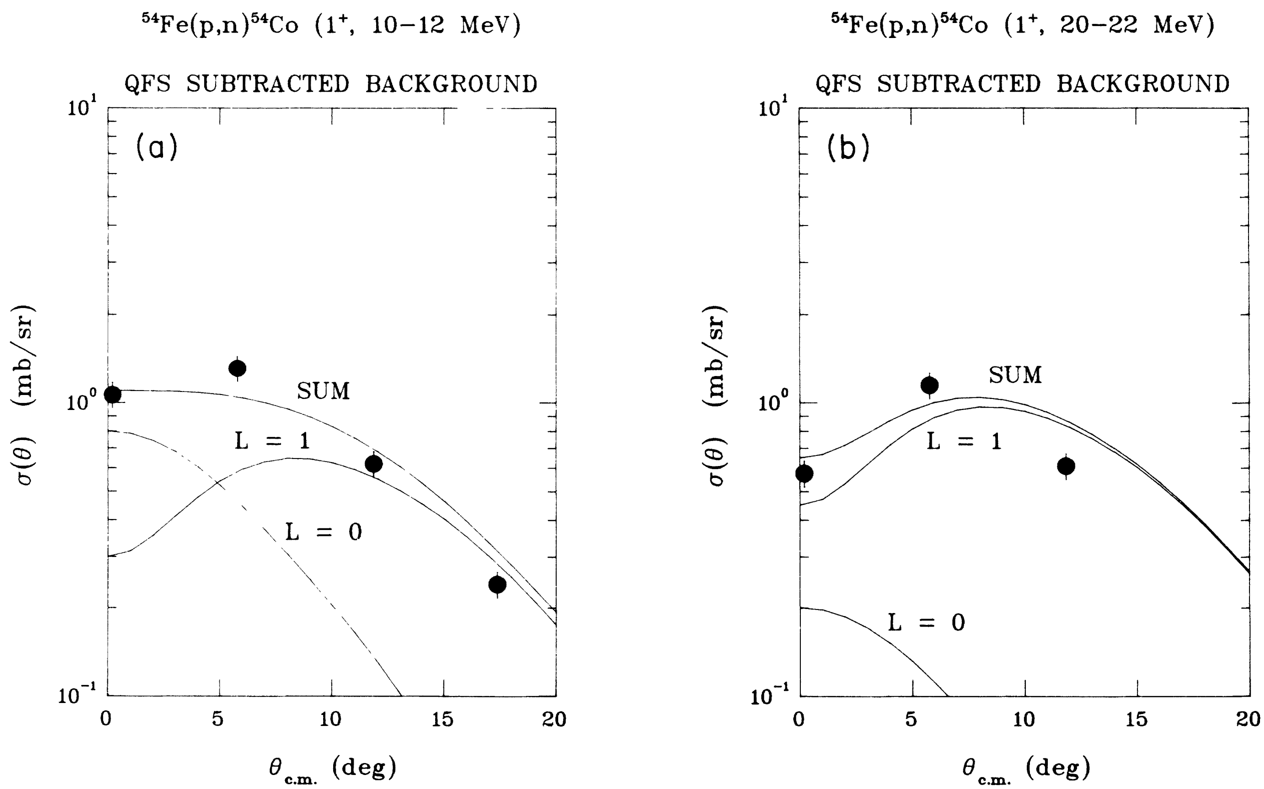

FIG. 7. Multipole decompositions of the angular distributions in the $E_x=10$ to 12 and 20 to 22 MeV intervals of the QFS subtracted "residual" background (see text).

angle spectra, the GTGR and the giant $\Delta L=1$ resonance disappear and the QFS calculations reproduce the shape of the continua very well.

The GT strength above the calculated QFS background is obtained from a "multipole decomposition" of the residual spectra. The fitted peaks and the QFS background are subtracted to obtain the "residual" spectra. These spectra were binned in 2 MeV intervals and angular distributions were plotted for each interval. Two such angular distributions are shown in Fig. 7. These angular distributions were then fit with "standard" $\Delta l=0$, 1, and 2 shapes. The $\Delta l=0$ shape was taken from the DWIA calculation for the largest 1^+ state at $E_x=10.1$ MeV, using the $1f$-$2p$ wave functions described below.[19] The $\Delta l=1$ shape was taken as the weighted average shape of the four possible (single step) $\Delta l=1$ transitions in this reaction, viz., 0^+ to 0^-, 1^- (with and without spin flip), or 2^-. The final four states were described as the coherent-state wave functions for these transitions in a particle-hole basis using the s-d and f-p shells plus the $g_{9/2}$ orbital; this basis yields 14 possible $1p$-$1h$ configurations. The $\Delta l=2$ shape was taken to be that for a 0^+ to 3^+ transition; the separation of $\Delta l=0$ and $\Delta l=1$ near 0° is not sensitive to this shape. DWIA calculations were performed for several different excitation energies in order to take into account the change of shape of each multipole with increasing momentum transfer.

The results of the multipole fits are shown for two intervals in Fig. 7. Because these fits are not unambigious, we estimate an uncertainty in the $\Delta l=0$ contribution at 0° to be $\pm 30\%$. The results from this analysis are presented in Table II. One sees that the $\Delta l=0$ contribution from this residual background is a maximum in the 8 to 10 MeV interval, underneath the GTGR. Because the QFS calculations are constrained to pass through the continuum near 25 MeV, the $\Delta l=0$ contributions go to zero at that point. The $\Delta l=0$ contributions from each interval are extrapolated to the same momentum transfer as the 0^+, IAS transition and converted to B(GT) units in the same manner as for the discrete peaks as described above. The summed B(GT) contribution from this residual background is $B(\mathrm{GT}-)=1.5\pm 0.5$, which is 26% of the peak strength. The net amount, from both discrete peaks and this "residual" background, is $\sum_0^{24\,\mathrm{MeV}} B(\mathrm{GT}-)=7.5\pm 0.7$. We note that this combined strength represents an analysis that is similar to that performed for this same reaction by Rapaport *et al.*[8] at 160 MeV, and also by Vetterli *et al.*[7] at 300 MeV. In both of these works, they performed multipole decompositions which included the background and continuum (up to 40 MeV). The decompositions they obtained indicated the $\Delta l=0$ contribution to be small above 20 MeV and looks similar to the combined result obtained here. Rapaport *et al.* obtained a summed GT strength $\sum_0^{40\,\mathrm{MeV}} B(\mathrm{GT}-)=7.8\pm 1.9$; Vetterli *et al.* obtained 7.5 ± 1.2. Our combined result is in excellent agreement with both of these values.

If we take our combined result together with the $B(\mathrm{GT}+)$ value from the (n,p) studies, we obtain the lower limit

$$\sum_0^{24\,\mathrm{MeV}} B(\mathrm{GT}-)-\sum_0^{10\,\mathrm{MeV}} B(\mathrm{GT}+)=7.5-3.1$$

$$=4.4\pm 0.9\ , \qquad (3)$$

which is 73 $(\pm 15)\%$ of the simple sum rule.

B. GT strength in the full background

Finally, we performed a multipole decomposition of the full background and continuum, without a QFS subtraction. The above analysis ignores GT strength in the QFS continuum and is probably an underestimate of the total GT strength. This analysis considers the full background and continuum, but necessarily ignores the fact

TABLE II. Experimental $\Delta l=0$ and B(GT) strength in the QFS subtracted residual background and continuum.

E_x (MeV)	$\sigma_{\Delta l=0}(0°)$ (mb/sr)	$\sigma_{\Delta l=0}(@q=q_{\mathrm{IAS}})$ (mb/sr)	B_{pn}(GT)
0–2	0	0	0
2–4	0	0	0
4–6	0.48	0.51	0.116
6–8	1.10	1.24	0.283
8–10	1.18	1.39	0.317
10–12	0.53	0.67	0.153
12–14	0.31	0.42	0.095
14–16	0.37	0.54	0.123
16–18	0.54	0.86	0.196
18–20	0.39	0.68	0.155
20–22	0.19	0.36	0.081
22–24	0.06	0.11	0.025
>24	≈ 0	0	0
			$\Sigma=1.55\pm 0.52$

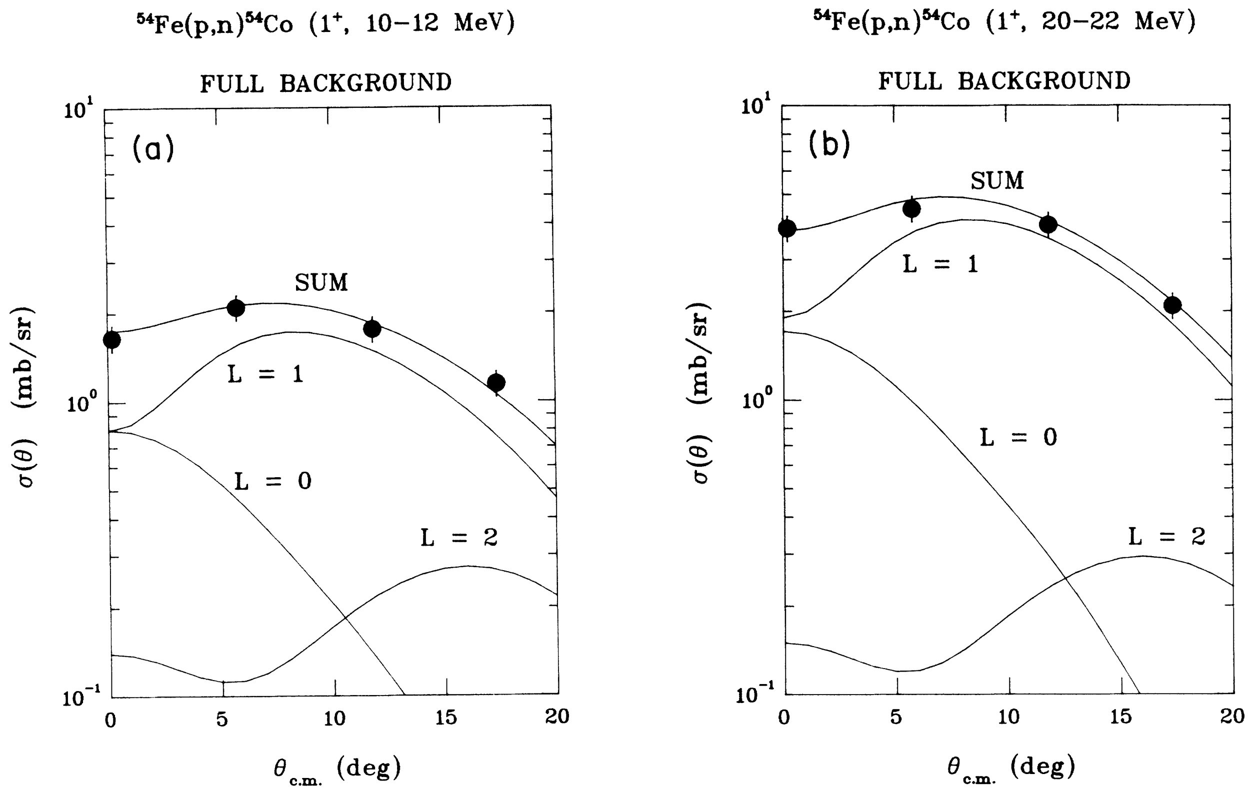

FIG. 8. Multipole decompositions of the angular distributions in the $E_x = 10$ to 12 and 20 to 22 MeV intervals of the "full" background (see text).

that the $\Delta l = 0$ signature of GT strength is lost in QFS. Thus, this analysis is an overestimate of GT strength in this region.

The fitted discrete peaks were subtracted from the TOF spectra to obtain the background and continuum. These spectra were then binned in 2 MeV intervals, and angular distributions were plotted for each interval similar to the above analysis. These angular distributions were then fit with the same "standard" $\Delta l = 0$, 1, and 2 shapes described above to obtain a multipole decomposition. Two such decompositions are shown in Fig. 8. The $\Delta l = 0$ and GT strengths obtained from these decompositions are presented in Table III. One sees that the amount of GT strength so obtained in each interval is greater than it was in the earlier analyses of the "residual" background, as expected. Note also that although the $\Delta l = 0$ contribution may peak near 18–20 MeV, it has by no means vanished at the highest energy bin available (viz., 22–24 MeV). Thus, even more GT strength would be obtained at higher excitation energies from this

TABLE III. Experimental $\Delta l = 0$ and B(GT) strength in the full background and continuum.

E_x (MeV)	$\sigma_{\Delta l=0}(0^\circ)$ (mb/sr)	$\sigma_{\Delta l=0}(@q=q_{\rm IAS})$ (mb/sr)	B_{pn}(GT)
0–2	0	0	0
2–4	0	0	0
4–6	0.40	0.43	0.098
6–8	0.84	0.95	0.216
8–10	0.7	0.83	0.189
10–12	0.8	1.01	0.230
12–14	1.0	1.36	0.310
14–16	1.2	1.78	0.405
16–18	1.6	2.56	0.583
18–20	2.0	3.46	0.788
20–22	1.7	3.34	0.760
22–24	1.6	3.16	0.719
			$\Sigma = 4.30 \pm 1.29$

analysis if the data were available; nevertheless, the amount of GT strength obtained here is $B(\mathrm{GT}-)=4.3\pm1.3$. The uncertainty is estimated to be $\pm30\%$ and is the uncertainty for the multipole decomposition only, and does not reflect any uncertainty in the procedure itself. If we combine this result with the GT strength obtained in discrete peaks, we have $\sum_0^{24\,\mathrm{MeV}} B(\mathrm{GT})=6.0+4.3=10.3\pm1.4$. If we now take this together with the result from the (n,p) studies, we obtain for the lower limit

$$\sum_0^{24\,\mathrm{MeV}} B(\mathrm{GT}-) - \sum_0^{10\,\mathrm{MeV}} B(\mathrm{GT}+) = 10.3-3.1 = 7.2\pm1.5\ , \quad (4)$$

which is 120 (±25)% of the simple sum rule.

VI. COMPARISON WITH SHELL-MODEL CALCULATIONS

Besides comparing the GT strength observed experimentally with the simple sum rule, it is worthwhile to compare the distribution of this strength with that predicted by a realistic shell-model calculation. For GT strength in $A=54$ nuclei, a realistic basis would be the $1f$-$2p$ shell, which should encompass all significant degrees of freedom. If one were to perform a shell-model calculation for all possible 1^+ states, considering 14 particles in the $1f$-$2p$ shells, millions of states are possible;[27] obviously, such a calculation is impossible and some truncation must be applied. The truncation considered here is the same as that used earlier for calculating GT strength in the $A=48$ and 51 mass systems.[4,27] The basis considered is

$$(f_{7/2})^{14}+(f_{7/2})^{13}(f_{5/2},p_{3/2},p_{1/2})^1 \ .$$

In this basis, there are 37, 1^+ states. The shell-model calculations were performed with the code OXBASH,[28] with matrix elements obtained from the works of Van Hees and Glaudemans,[29] Koops and Glaudemans,[30] plus MSDI.[31] Similar calculations for the $A=48$ and 51 systems were seen to reproduce the relative distribution of GT strength well.

The results of the shell-model calculation for the ^{54}Fe$(p,n)^{54}$Co reaction are shown compared with the experimental results for discrete peaks (from Table I) in Fig. 9. The one-body transition densities (OBTDs) from the shell-model calculations were used together with free-nucleon values of the GT two-body operator,[32] to obtain predicted $B(\mathrm{GT}-)$ values for each transition. The general distribution of GT strength is seen to be reproduced well. A relatively strong excitation is predicted near $E_x=1$ MeV, corresponding to the observed state at 0.94 MeV. A gap of a few MeV is predicted just above this low-lying state, followed by a broad distribution near 5 MeV to about 14 MeV of excitation, with the largest single state predicted to be near $E_x=10$ MeV; all of these predictions agree qualitatively with the experimental results. The fact that not as many GT states are predicted as observed is due to the truncation of the model space.

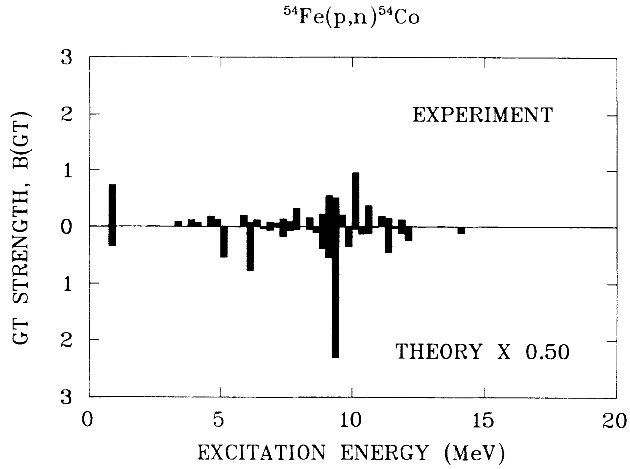

FIG. 9. Comparison of a $1f$-$2p$ shell-model prediction of the $B(\mathrm{GT}-)$ spectrum in the ^{54}Fe$(p,n)^{54}$Co reaction with the experimental $B(\mathrm{GT}-)$ spectrum for strength in discrete peaks. Both the experimental and theoretical results are summed in 0.25 MeV intervals.

The significant problem observed in this comparison between the shell-model predictions and the experimental results is in the absolute strengths. The shell-model prediction is more than twice as large as the experimental result for strength observed in discrete peaks. The shell-model calculation predicts a total $B(\mathrm{GT}-)=14.01$. The amount seen experimentally in discrete peaks is, from Table I, $B(\mathrm{GT}-)=5.95$, which is 43% of the shell-model prediction. (If one considers also the GT strength from the multipole decomposition of the QFS subtracted background, this fraction increases to 54%.) This same problem was observed also for shell-model predictions compared with the observed $B(\mathrm{GT}+)$ strength in the ^{54}Fe(n,p) reaction.[7] This over prediction is due to the necessary truncation; for example, Vetterli *et al.*[7] report that a calculation by Muto,[33] which considers ($2p$-$2h$) excitations in the target nucleus, is able to reduce the theoretical estimate for the ^{54}Fe(n,p) reaction by nearly a factor of 2. Similarly, we find[34] that a full $1f$-$2p$ shell calculation for GT strength in the ^{45}Sc$(p,n)^{45}$Ti reaction (where the number of 1^+ states is "only" about 9500) is in good agreement with both the distribution and magnitude of observed strength. The reduction in strength for the more complete calculations comes from configuration mixing with the more complicated configurations and has the result of moving much of the strength from the peaks up into the continuum. This effect is just the one discussed by Bertsch and Hammomoto,[21] and mentioned in the Introduction to this paper.

VII. CONCLUSIONS

The ^{54}Fe$(p,n)^{54}$Co reaction was studied at 135 MeV with an energy resolution of 245 KeV. The forward-angle spectra are dominated by 1^+ excitations, which are interpreted as GT strength in this reaction. The GT strength is observed to be highly fragmented; GT strength is identified in more than 30 states. The GT strength is obtained relative to the Fermi strength assumed to be concentrated in the 0^+, isobaric-analog ground state. The $B(\mathrm{GT}-)$ strength is extracted for discrete states and also from the background in two ways. The strength so obtained is combined with the $B(\mathrm{GT}+)$ strength obtained from the $^{54}\mathrm{Fe}(n,p)$ reaction by Vetterli *et al.*[7] and compared with the simple sum rule. Because only a few measurements of $B(\mathrm{GT}+)$ have been performed, this reaction is an important case to obtain good (p,n) measurements and analyses in order to compare with the sum rule.

We find that the total strength observed in discrete states in the (p,n) reaction is $\sum_0^{14\,\mathrm{MeV}} B(\mathrm{GT}-)=6.0\pm0.4$. If we combine this with the result from the (n,p) measurements of $\sum_0^{10\,\mathrm{MeV}} B(\mathrm{GT}+)=3.1\pm0.6$, we obtain a lower limit of only 48($\pm$12) percent of the simple $3(N-Z)$ sum rule. Recognizing that there is GT strength also in the background and continuum, we performed a multipole decomposition of these regions in order to try to extract GT strength. Noting that the continuum is dominated by quasifree scattering (QFS) [i.e., the (p,pn) reaction], we subtracted a DWIA calculation of the QFS, normalized to the observed continuum near 25 MeV. A multipole decomposition of the "residual" background and continuum was performed with standard shapes for the different l transfers. The $\Delta l=0$ contribution was interpreted as GT strength. These analyses yielded an additional $B(GT-)=1.55\pm0.52$ which, when added to the strength from discrete peaks and combined with the $B(\mathrm{GT}+)$ value, then yields a lower limit of 73 ($\pm$15%) of the sum rule. Finally, a similar multipole decomposition of the "full" background and continuum (up to 25 MeV) indicates that the entire sum rule may be satisfied. The results observed here are in agreement with a general trend noted earlier,[4] viz., that in light nuclei about 65% of the simple sum rule strength is observed in discrete peaks, but that in heavier nuclei this fraction decreases to below 50%. This decrease is due plausibly to the increased effects of configuration mixing, and we see that multipole decomposition of the residual background above a quasifree scattering calculation brings the observed GT strength back up to about 65% for the heavier nuclei.

It is important to keep in mind that all of these results are with respect to the value reported for $B(\mathrm{GT}+)$. If there is additional GT+ strength beyond that reported in Ref. 7, then the percentages obtained above will be smaller. In fact, Figs. 7–10 of Ref. 7 show that there may be considerable $\Delta L=0$ strength above their cutoff at $E_x=10$ MeV. This additional strength was not included in the reported $B(\mathrm{GT}+)$ value because of the large uncertainties involved in the analysis. Because of the uncertain bound on the reported $B(\mathrm{GT}+)$ value, the percentages of the simple sum rule obtained here are lower limits only with respect to the GT− strength.

The observed distribution of GT strength was compared with a truncated $1f$-$2p$ shell-model calculation. The observed and calculated distributions are in good agreement in terms of the distribution of relative strength; however, the predicted strength is more than twice that observed in discrete peaks. The good agreement for the distribution indicates that the shell-model calculation includes the dominant $1p$-$1h$ states that are excited strongly by the impulsive (p,n) reaction. The problem with the predicted amount of strength is due to the severe truncation which neglects configuration mixing with more complicated states.

These measurements provide the best resolution yet available for the Gamow-Teller giant resonance (GTGR) in the $^{54}\mathrm{Fe}(p,n)^{54}\mathrm{Co}$ reaction, still at an energy where the reaction is believed to be dominated by a single-step impulsive mechanism. These results allow for the GT strength in discrete peaks to be extracted more accurately. Possible GT strength in the background and continuum remains uncertain. The problems with the extraction of such background and continuum strength are not due to the limitations of the experimental resolution and are model dependent.

[1]B. A. Brown, W. Chung, and B. H. Wildenthal, Phys. Rev. Lett. **40**, 1631 (1978); B. A. Brown and B. H. Wildenthal, Phys. Rev. C **28**, 2397 (1983).

[2]J. Rapaport, Can. J. Phys. **65**, 574 (1987).

[3]T. N. Taddeucci, C. A. Goulding, T. A. Carey, R. C. Byrd, C. D. Goodman, C. Gaarde, J. Larsen, D. Horen, J. Rapaport, and E. Sugarbaker, Nucl. Phys. **A469**, 125 (1987).

[4]B. D. Anderson, T. Chittrakarn, A. R. Baldwin, C. Lebo, R. Madey, P. C. Tandy, J. W. Watson, B. A. Brown, and C. C. Foster, Phys. Rev. C **31**, 1161 (1985).

[5]R. Madey, B. S. Flanders, B. D. Anderson, A. R. Baldwin, C. Lebo, J. W. Watson, S. M. Austin, A. Galonsky, B. H. Wildenthal, and C. C. Foster, Phys. Rev. C **35**, 2011 (1987).

[6]K. I. Ikeda, S. Fujii, and J. I. Fujita, Phys. Lett. **3**, 271 (1963).

[7]M. C. Vetterli, O. Hausser, W. P. Alford, D. Frekers, R. Helmer, R. Henderson, K. Hicks, K. P. Jackson, R. G. Jeppesen, C. A. Miller, M. A. Moinester, K. Raywood, and S. Yen, Phys. Rev. Lett. **59**, 439 (1987); M. C. Vetterli, O. Hausser, R. Abegg, W. P. Alford, A. Celler, D. Frekers, R. Helmer, R. Henderson, K. H. Hicks, K. P. Jackson, R. G. Jeppesen, C. A. Miller, K. Raywood, and S. Yen, Phys. Rev. C **40**, 559 (1989).

[8]J. Rapaport, T. Taddeucci, T. P. Welch, C. Gaarde, J. Larsen, D. J. Horen, E. Sugarbaker, P. Kong, C. C. Foster, C. D. Goodman, C. A. Goulding, and T. Masterson, Nucl. Phys. **A410**, 371 (1983).

[9]C. D. Goodman, C. C. Foster, M. B. Greenfield, C. A. Goulding, D. A. Lind, and J. Rapaport, IEEE Trans Nucl. Sci. **NS-26**, 2248 (1979).

[10]A. R. Baldwin and R. Madey, Nucl. Instrum. Methods **171**, 149 (1980).

[11]R. Madey *et al.*, Nucl. Instrum. Methods **214**, 401 (1983).

[12]R. Cecil, B. D. Anderson, and R. Madey, Nucl. Instrum. Methods **161**, 439 (1979).

[13]J. W. Watson, B. D. Anderson, A. R. Baldwin, C. Lebo, B. Flanders, W. Pairsuwan, R. Madey, and C. C. Foster, Nucl. Instrum. Methods **215**, 413 (1983).

[14]J. D'Auria, M. Dombsky, L. Moritz, T. Ruth, G. Sheffer, T. E. Ward, C. C. Foster, J. W. Watson, B. D. Anderson, and J. Rapaport, Phys: Rev. C **30**, 1999 (1984).

[15]P. R. Bevington, K. G. Kibler, and B. D. Anderson, Case Western Reserve University Report No. C00-1573-63, 1969 (unpublished); P. R. Bevington, *Data Reduction and Error Analysis for the Physical Sciences* (McGraw-Hill, New York, 1969), p. 237.

[16]Program DWBA70, R. Schaeffer and J. Raynal (unpublished); Extended version DW81 by J. R. Comfort (unpublished).

[17]M. A. Franey and W. G. Love, Phys. Rev. C **31**, 488 (1985).

[18]P. Schwandt, H. O. Meyer, W. W. Jacobs, A. D. Bacher, S. E. Vigdor, M. D. Kaitchuck, and T. R. Donoghue, Phys. Rev. C **26**, 55 (1982).

[19]B. A. Brown (private communication).

[20]F. Osterfeld, Phys. Rev. C **26**, 762 (1982).

[21]G. F. Bertsch and I. Hamamoto, Phys. Rev. C **26**, 1323 (1982).

[22]B. D. Anderson, A. R. Baldwin, A. M. Kalenda, R. Madey, J. W. Watson, C. C. Chang, H. D. Holmgren, R. W. Koontz, and J. R. Wu, Phys. Rev. Lett. **46**, 226 (1981); A. M. Kalend, B. D. Anderson, A. R. Baldwin, R. Madey, J. W. Watson, C. C. Chang, H. D. Holmgren, R. W. Koontz, J. R. Wu, and M. Machner, Phys. Rev. C **28**, 105 (1983).

[23]J. R. Wu, Phys. Lett. **91B**, 169 (1980).

[24]P. A. Wolff, Phys. Rev. **87**, 434 (1952).

[25]J. W. Watson, P. J. Pella, M. Ahmad, B. S. Flanders, N. S. Chant, P. G. Roos, D. W. Devins, and D. L. Friesel, J. Phys. (Paris) Colloq. **45**, C4-91 (1984).

[26]L. R. B. Elton and A. Swift, Nucl. Phys. **A94**, 52 (1967).

[27]J. Rapaport, R. Alarcon, B. A. Brown, C. Gaarde, J. Larsen, C. D. Goodman, C. C. Foster, D. Horen, T. Masterson, E. Sugarbaker, and T. N. Taddeucci, Nucl. Phys. **A427**, 332 (1984).

[28]Computer code OXBASH, B. A. Brown, A. Etchegoyen, W. D. M. Rae, and N. S. Godwin (unpublished).

[29]A. G. M. Van Hees and P. W. M. Glaudemans, Z. Phys. A **303**, 267 (1981).

[30]J. E. Koops and P. W. M. Glaudemans, Z. Phys. A **280**, 181 (1977).

[31]MSDI: Modified surface delta interaction, B. A. Brown, Michigan State University (private communication).

[32]Computer code TRANS, B. A. Brown, Michigan State University (private communication).

[33]K. Muto, Nucl. Phys. **A451**, 481 (1986).

[34]M. Mostajabboda'vati, Ph.D. Dissertation, Kent State University, 1989.