Gamow-Teller strength in the $^{18}O(p,n)^{18}F$ reaction at 135 MeV

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The distribution of Gamow-Teller strength in the $^{18}O(p,n)^{18}F$ reaction was studied at a bombarding energy of 135 MeV. Five 1^+, $T=0$ states are identified below $E_x=7$ MeV and a concentration of 1^+ states of presumed $T=1$ character is observed between $E_x=9.5$ and 12 MeV. Approximately 82% of the 1^+ strength is concentrated into the ground-state transition and only 5.5% is seen in the $T=1$ component. Normalization of the ground-state transition to the known Gamow-Teller matrix element from the analogous beta decay of ^{18}Ne allows the (p,n) cross sections to be related to the Gamow-Teller strength. The resulting total Gamow-Teller strength observed in the (p,n) reaction is about two-thirds of the minimum value required by the sum rule for a $T=1$ nucleus. This result is in reasonable agreement with the total Gamow-Teller strength predicted from a shell-model calculation which uses empirically renormalized single-particle Gamow-Teller matrix elements. The concentration of the $T=0$ strength predominantly into the ground state and the observed ratio of $T=1$ to $T=0$ strength also are consistent with these calculations.

NUCLEAR REACTIONS $^{18}O(p,n)^{18}F$, $E=135$ MeV; neutron spectra measured in $\sim 3°$ steps between 0° and 69°; angular distributions extracted for separate transitions. Strengths of forward-peaked transitions compared with shell-model predictions of Gamow-Teller strength.

At energies from about 100 to 500 MeV, the isovector nucleon-nucleon effective interaction is dominated at low-momentum transfer by the spin-transfer term.[1] Goodman *et al.*[2,3] confirmed that forward-angle (p,n) spectra are dominated by such spin-transfer transitions and showed[4] that the cross sections to different final states are proportional to the squares of the corresponding Gamow-Teller (GT) matrix elements as determined from beta decay. GT type transitions that are energetically inaccessible to beta decay can be studied with the (p,n) reaction; thus, the (p,n) measurements extend the types of spectroscopic studies which are typified by beta decay.

In the present work, we analyze the forward-angle spectra for the $^{18}O(p,n)^{18}F$ reaction at 135 MeV, extract absolute cross sections for the states observed, and determine the location and intensity of the GT strength in ^{18}F. We find that the GT strength is concentrated predominantly in the $T=0$ ground state of ^{18}F, and that only a small fraction of the strength is seen in the $T=1$ isospin component. These results are similar to those observed in the $^{42}Ca(p,n)^{42}Sc$ reaction by Goodman *et al.*[5] The total GT strength observed, normalized to the known analog beta decay of the $T=0$, 1^+ ground state of ^{18}F, is approximately two-thirds of the minimum strength required by the GT sum rule. This fraction is larger than that reported[2] for various medium and heavy nuclei, but is consistent with that seen in the $^{14}C(p,n)^{14}N$ reaction.[6]

The experiment was performed at the Indiana

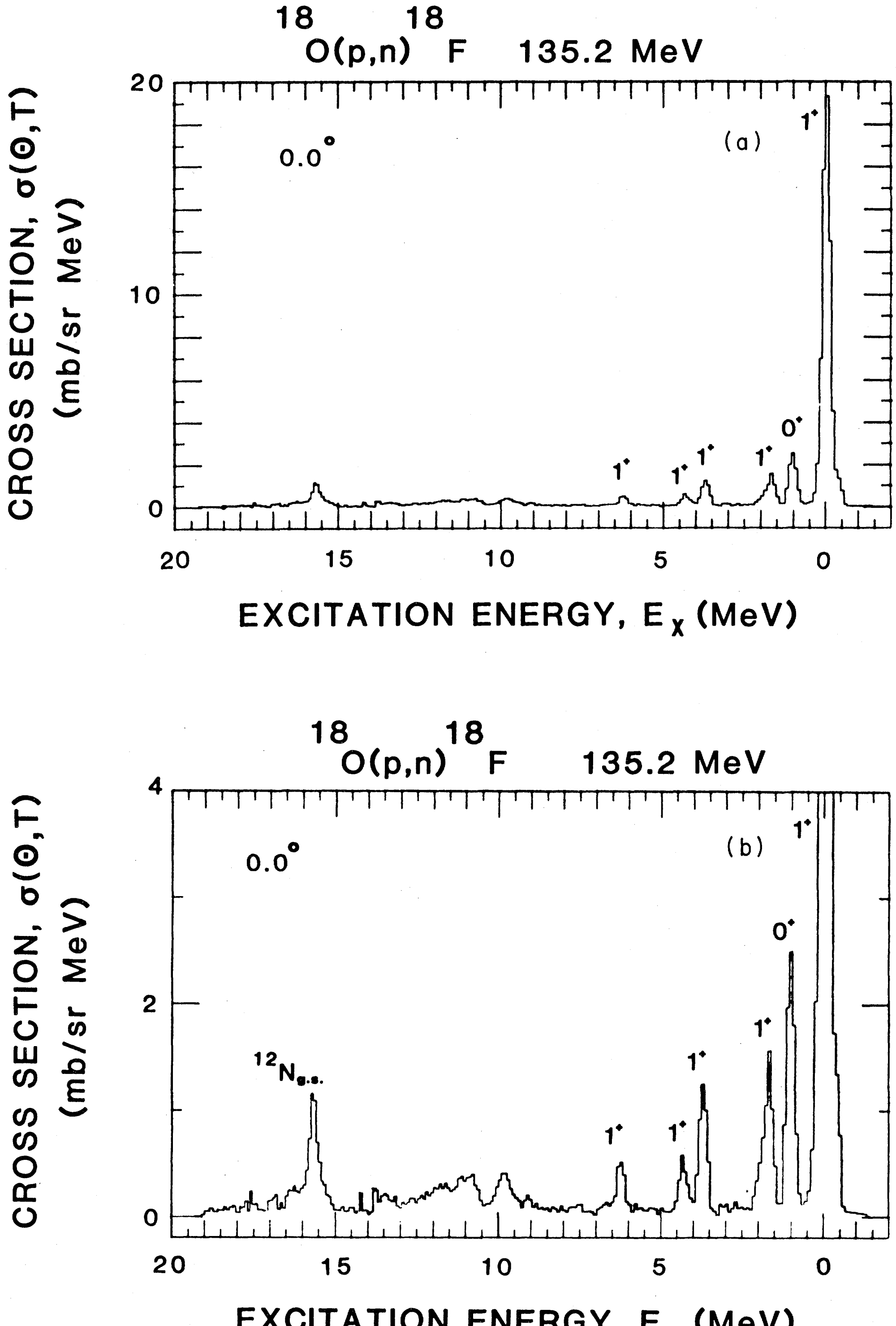

FIG. 1. Excitation energy spectrum at 0° for the $^{18}O(p,n)^{18}F$ reaction at 135 MeV. (a) vertical scale adjusted to display the sizes of the states relative to the strong ground-state transition, and (b) vertical scale expanded to display weaker transitions to states at higher excitation energies.

University Cyclotron Facility with the beam-swinger system. Neutron energies were measured by the time-of-flight technique. The neutrons were detected in large-volume, mean-timed neutron counters with a 90.9 m flight path. Overall timing resolutions of about 0.5 ns provided energy resolutions (for ~120 MeV neutrons) of about 320 keV. The target contained 38.8 mg/cm^2 SiO_2 with 95.7% ^{18}O. The silicon was natural in abundance with 4.7% ^{29}Si and 3.1% ^{30}Si. [Sometime after this experiment, the target was found to contain a substantial amount (~43%) of H_2O, hygroscopically absorbed by the SiO_2.] Absolute cross sections were extracted using calculated neutron detector efficiencies.[7] The procedure was checked by measuring the $^{12}C(p,n)^{12}N$ ground-state (g.s.) reaction cross section, which was compared[8] with the analog $^{12}C(p,p')^{12}C$ (15.11 MeV) cross section. The experimental arrangement and data reduction methods are described in more detail by Fazely *et al.*[9] The Si and ^{16}O backgrounds were subtracted, channel-by-channel, in the time-of-flight (TOF) spectra using Si(p,n) and $^{16}O(p,n)$ TOF spectra obtained during the same experimental run. The Si subtraction was normalized to the strong transition to the 1^+ state at $E_x=2.1$ MeV in ^{28}P, and the ^{16}O subtraction to the strong transition to the 2^- state at $E_x=0.42$ MeV in ^{16}F. These normalizing transitions are observed in the $^{18}O(p,n)^{18}F$ spectra at excitation energies in ^{18}F of 14.9 and 14.3 MeV, respectively. The absolute cross section measurements are estimated to be accurate to $\pm 15\%$, as discussed below.

Figure 1 is the excitation energy spectrum at 0°. The excitation energy above $E_x=13$ MeV involves large Si and O subtractions and is probably unreliable. Since no ^{28}Si or ^{16}O contaminant peaks exist below $E_x=12.7$ MeV, the spectrum is a reliable representation of the states in ^{18}F up to this excitation energy. The peak observed at an excitation energy of about 15.7 MeV is attributed to the $^{12}C(p,n)^{12}N_{g.s.}$ transition arising from (~5%) carbon contamination in the target. This peak provided a useful check on the energy calibration, which was established relative to the strong 1^+ ground-state transition in ^{18}F.

The transition to the 1^+ g.s. is seen to dominate the spectrum of Fig. 1. Separate transitions to four other known[10] $T=0$, 1^+ states, as well as the $T=1$, 0^+ isobaric analog state (IAS) at $E_x=1.04$ MeV, are seen also. No 1^+ states above $E_x=7$ MeV are reported in the ^{18}F compilation.[10] Figure 2 shows the extracted differential cross sections for the 1^+ g.s. The curves represent the result of a DWIA calculation described below. Even though this 1^+ transition is very forward-peaked, the differential cross section could be extracted out to about 45 deg, be-

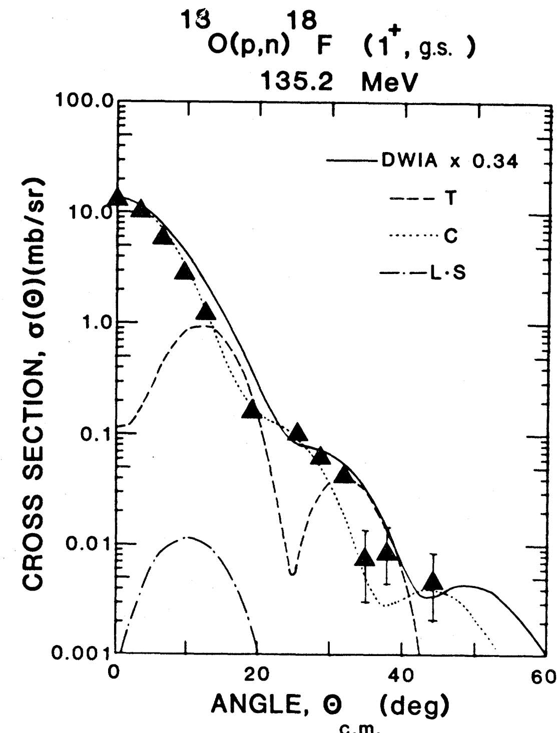

FIG. 2. Comparison of the measured angular distribution for the $^{18}O(p,n)^{18}F$ g.s. transition with a DWIA calculation (see text).

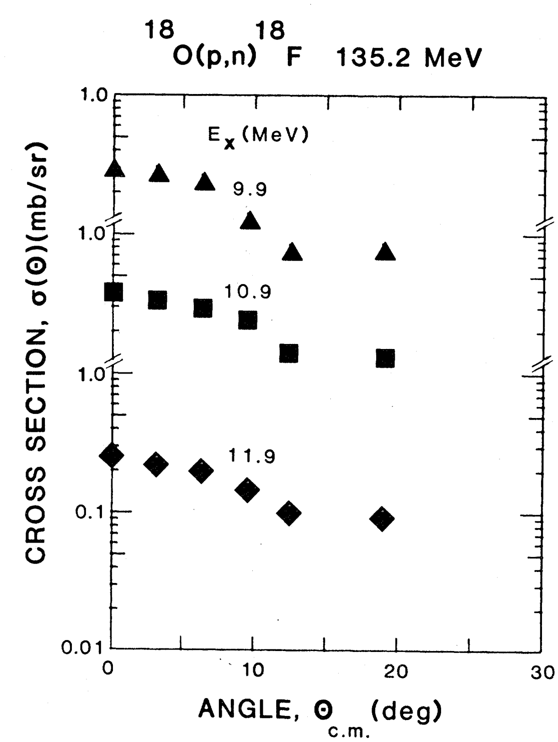

FIG. 3. Meaured angular distributions for the three bumps observed in the $^{18}O(p,n)^{18}F$ reaction at excitation energies between 9.5 and 12 MeV.

cause the transition was resolved cleanly in this experiment. At higher excitation energies, we observe strength in the 0° spectrum distributed among three broad bumps between 9.5 and 12 MeV. Figure 3 shows the angular distributions extracted for these three bumps. Although these distributions do not decrease with angle as rapidly as that for the ground-state transition, they are peaked at 0°. The strength observed at wider angles is apparently from other structures in the nuclear continuum, which competes with the decreasing strength of the 1^+ transitions. The forward-peaked strength observed near 10 MeV indicates either 0^+ or 1^+ states in ^{18}F. The dominance of the spin-flip term in the nucleon-nucleon effective interaction at these energies would make these likely candidates for the $T=1$, 1^+ strength. These states cannot be $T=2$ excitations because the first $T=2$ state in ^{18}O (the analog of the ground state of ^{18}N) is known[10,11] to be at $E_x=16.38$ MeV, which would correspond to about 17.4 MeV in ^{18}F. Thus, $T=2$, 1^+ strength must be at least 5 MeV higher than the forward-peaked strength observed between 9.5 and 12 MeV.

Absolute cross sections at 0° are presented in Table I for transitions peaked at 0°. These cross sections are estimated to be accurate to $\pm 20\%$. The dominating source of uncertainty is the target thickness ($\pm 15\%$). This uncertainty arises because the target was found to contain water absorbed hygroscopically by the original SiO_2 target. Although the target was weighed immediately after preparation, we checked the possibility that some water might have been absorbed before weighing by comparing extracted cross sections for the strongly-excited 6^- state in the ^{28}Si$(p,n)^{28}$P reaction with a natural Si target[12] with the SiO_2 target. This comparison indicated that the extracted cross section from SiO_2 was accurate to $\pm 15\%$ and verifies the amount of SiO_2 to that accuracy. Other sources of uncertainty are estimated to be relatively small, including the efficiency determination ($\pm 8\%$), beam normalization ($\pm 5\%$), and neutron attenuation corrections ($\pm 5\%$). The *relative* accuracy of the 0° cross sections in Table I is estimated to be $\pm 5\%$. This uncertainty includes counting statistics ($\lesssim 3\%$) and background subtractions ($\sim 5\%$).

The angular distribution for the g.s. transition is presented in Fig. 2 and compared with a DWIA calculation, performed with the code DWBA70.[13] The calculation used harmonic-oscillator bound-state wave functions [with an oscillator parameter $b \equiv (\hbar/m\omega)^{1/2} = 1.75$ fm]. The optical model parameters of Comfort and Karp[14] for ^{12}C at 135 MeV were extrapolated to ^{18}O on the basis of an $A^{1/3}$ dependence. The effective interaction assumed was the 140 MeV interaction of Love and Franey,[1] and the one-body transition density matrix elements were taken from the shell-model calculation described below. The agreement in shape is seen to be good. A normalization factor of 0.34 is required to make the calculations agree in magnitude with the experimental results.

The strength observed in the 1^+ excitations can be normalized to the available analog beta decays to the first two 1^+ states. The ^{18}O$(p,n)^{18}$F reaction is the analog of the ^{18}Ne$(\beta^+)\rightarrow^{18}$F beta decay. The accepted values of logft for the beta decays to the ground and 1.7 MeV states of ^{18}F are 3.088 ± 0.003 and 4.38 ± 0.05, respectively.[15] On the basis of the relationship from Wilson *et al.*[16] between Fermi (F) and Gamow-Teller (GT) matrix elements and observed ft values, viz.,

$$|M_F|^2 + 1.56\,|M_{GT}|^2 = \frac{6163.4}{ft}\,, \tag{1}$$

it is possible to extract the GT matrix element for

TABLE I. Experimental 0° cross sections and predicted Gamow-Teller strength distributions.

Experimental				Wildenthal and Chung			
Final state E_x (MeV)	$J;T$	$\sigma(0°)$ (mb/sr)	B_{exp}(GT)	Final state E_x (MeV)	$J;T$	B_{fn}(GT)	B_{emp}(GT)
0.00	$1^+;0$	13.59	3.23	0.00	$1^+;0$	5.463	3.260
1.04	$0^+;1$	1.49					
1.70	$1^+;0$	0.82	0.195	4.01	$1^+;0$	0.005	0.003
3.72	$1^+;0$	0.78	0.185	6.32	$1^+;0$	0.047	0.080
4.35	$1^+;0$	0.37	0.088	9.36	$1^+;0$	0.030	0.0005
6.26	$1^+;0$	0.26	0.062	15.01	$1^+;0$	0.018	0.008
9.9	$(1^+;1)$	0.25	0.059				
10.9	$(1^+;1)$	0.37	0.088	10.69	$1^+;1$	0.421	0.202
11.9	$(1^+;1)$	0.27	0.064	11.34	$1^+;1$	0.013	0.006
			$\sum=3.971$			6.000	3.560

these decays (which are pure GT). In this way, we obtain $B(\mathrm{GT})[=|M_{\mathrm{GT}}|^2]=3.23$ and 0.165 for the beta decays to the ground and 1.7 MeV state transitions, respectively. We note that Eq. (1) is expressed in units such that the value $B(\mathrm{GT})=3$ for the free neutron.

The ratio between the cross sections of the 1.7 MeV and the ground-state (p,n) transitions (listed in Table I) agrees well with the ratio of the GT strengths B(GT) for the beta decays to these two states obtained from Eq. (1), viz., 0.060($\pm$0.004) from (p,n) versus 0.051 ($\pm$0.006) from beta decay. If we normalize all our 0° (p,n) cross sections for 1^+ states so that the ground-state cross section yields the B(GT) value of that state in beta decay, we obtain the $B_{\mathrm{exp}}(\mathrm{GT})$ values listed in Table I. Thus, the 0° (p,n) spectrum implies $\sum B(\mathrm{GT})=\sum(1^+)=3.97$.

Now the sum rule for Gamow-Teller beta decay is[17]

$$S_{\beta^-}-S_{\beta^+}=3(N-Z)\ . \tag{2}$$

Since no β^+ transitions are possible for two neutrons outside a closed core, we would obtain

$$S_{\beta^+}=0 \text{ and } 3(N-Z)=S_{\beta^-}=\sum B(\mathrm{GT})=6\ . \tag{3}$$

We note that there can be contributions from core excitations in ^{18}O to the observed 1^+ strength. Transitions to three 1^+ states were observed in the ^{16}O$(p,n)^{16}$F reaction,[9] in agreement with (e,e') and $(\vec{p},\gamma)$ experiments[18,19] to the analog states in ^{16}O. The observed (p,n) cross section of 0.81 mb/sr to 1^+ states in ^{16}F corresponds to $B(\mathrm{GT})=0.19$, still assuming the relationship between a 135 MeV, 0° (p,n) cross section and the B(GT) for the ^{18}F g.s. transition. The correction to the sum rule indicated by the observed 1^+ strength in ^{16}F would be small (viz., $\sim 3\%$); however, the effect of the core correlations really remains uncertain. The two extra neutrons in ^{18}O likely produce additional polarization of the ^{16}O core, so that the estimate of core polarization effects based on ^{16}O may be unreliable. The effects of the additional core correlations are ambiguous.

In Table I, we present the peak locations and experimental B(GT) values for the observed 1^+ spectrum compared to theoretical predictions obtained from the shell-model calculations of Wildenthal and Chung.[20] These shell-model calculations employ a complete s-d basis and an effective Hamiltonian derived from adjustments of the Kuo $A=18$ s-d shell Hamiltonian[21] to obtain a best fit to energy levels of the $A=18-24$ nuclei. Thus all states in ^{18}F are two-particle states and are either $T=0$ or $T=1$. The theoretical B(GT) values were calculated by summing the products of each $j \to j'$ transition density with the corresponding reduced single particle matrix elements $\langle j' \| O_{\mathrm{GT}} \| j \rangle$. The theoretical strengths labeled $B_{\mathrm{fn}}(\mathrm{GT})$ were obtained by using the "free-nucleon" operator $O_{\mathrm{GT}}=\sigma\tau$, while the strengths labeled $B_{\mathrm{emp}}(\mathrm{GT})$ were obtained by using the empirical "single-particle" GT matrix elements determined by Brown, Chung, and Wildenthal[22] by fitting to 54 known GT β-decay strengths in s-d shell nuclei.

The "free-nucleon" predictions necessarily agree with the sum rule of Eq. (3). The "empirical" predictions do not, because the operator $\sigma\tau$ has been multiplied by a nonunity coefficient for each possible sd-shell one-body transition. The rationale for introducing this "effective" GT operator is that the agreement between experiment and the shell model is markedly better in relative terms than in absolute terms. Specifically, the theoretical predictions based on the half-life of the free neutron yield strengths which are systematically larger than observed; i.e., experimental GT beta decay strengths are "quenched" relative to "free-nucleon"-based shell model predictions. This quenching can be attributed in various degrees to the effects of restricting the model space to only one major oscillator shell and restricting the model constituents to be only and always neutrons and protons.

The "empirical" GT operator is particularly model dependent in that it is based on a normalization to data from the low-lying levels accessible to the Q values available in natural beta decay. Except for mass 17 and mass 18, the dominant GT strength tends to lie above the Q-value windows. Hence, the deduced empirical GT operator could merely be a compensation for the Chung-Wildenthal shell model wave functions incorrectly moving too much strength into the low-lying states. The (p,n) reaction, by virtue of its freedom from Q-value constraints, allows this possibility to be checked. Agreement between the complete B(GT) spectrum provided with the (p,n) study and the predictions based on the empirical GT operator can be taken not only as a confirmation of this theoretical approach, but also as confirmation that there is not a significantly greater amount of strength in the higher-lying states than predicted by the shell model calculations.

From Table I we see that the calculations predict that the GT strength is largely concentrated in the transition to the $T=0$ ground state and that only about 6% will be seen in the $T=1$ component. These predictions agree well with the measurements. Experimentally, about 82% of the total 1^+ strength is in the g.s. transition (compared to 91% predicted). We observe about 5% of the total 1^+ strength in what we assume to be $T=1$ components near 10 MeV, which is in good agreement with the predicted fraction. The excitation energies of these observed (assumed) $T=1$ states also agree reasonably well with the predictions. The largest differences between the predicted GT strengths and the observed 1^+ spectrum are for the strength and location of the $T=0$, 1^+ states other than the g.s. The shell-model prediction indicates that about 3% of the total strength will be in these states, and that they will range in excitation energies up to 15 MeV above the g.s. Experimentally, we see about 13% of the total 1^+ strength in these states and that they range in excitation energies only up to 6.3 MeV. (It cannot be ruled out, of course, that either of the forward-peaked states seen near 10 MeV is, in fact, $T=0$.) The spectrum of positive parity states in ^{18}F is much more dense than can be legitimately produced by $(sd)^2$ excitations alone.[23] In particular, the 1.70 MeV 1^+ state seems clearly based on 4p-2h configurations[24] and the importance of such excitations in treating many of the observed higher-lying 1^+ states is also crucial. The present experimental results indicate that the strength of the dominant ground-state transition is not only more spread into the other $(sd)^2$ 1^+ states than is predicted, but that it also is mixed into the basically core-excited states to an equivalent degree.

The near degeneracy of the centroids of the GT strength and the Fermi (IAS) strength together with the strong dominance of the $T=0$ component over the $T=1$ component observed here in the ^{18}O(p,n) reaction is similar to that observed recently in the ^{42}Ca(p,n) reaction.[5] As noted in Ref. 5, these features suggest the net effects of spin-orbit coupling are much less important than those expected from an independent particle j-j coupling shell model. The shell model calculations of Chung and Wildenthal predict (with the free-nucleon GT operator) a ratio of 1 to 13 for $\sum B(\text{GT})$, $T=1$ relative to $\sum B(\text{GT})$, $T=0$, while the j-j coupling limit of $(d_{5/2})^2_{J=0,T=1}$ for ^{18}O yields a ratio of 1 to 2.7. If the $T=1$, 0^+ target state were described by L-S coupling with only the $(n)^2_{L=0,S=0}$ configuration, then all the GT strength would reside in $T=0$ states. The observed ratio of 1 to 18 for $\sum B(\text{GT})$, $T=1$ to $\sum B(\text{GT})$, $T=0$ in the ^{18}O(p,n) reaction suggests that ^{18}O g.s. wave functions are dominated by $L=0$, $S=0$ coupling. The configuration of the 1^+ state receiving the GT strength would then be largely $L=0$, $S=1$ with the total spatial symmetry preserved. In this context, the near degeneracy of GT and Fermi strength is suggestive of an SU(4) supermultiplet for spin-isospin excitations. For the ^{18}O(p,n) reaction, about 80% of the GT strength is observed within one MeV of the Fermi strength; this result contrasts with most other light- and medium-weight nuclei where the centroids of GT and F strength are split by several MeV.

In summary, we find that the total GT strength observed in the ^{18}O$(p,n)^{18}$F reaction is about 67% of that expected from the simple sum rule. This fraction is higher than that observed in similar analyses for medium- and heavy-weight nuclei, but is consistent with that measured for the ^{14}C$(p,n)^{14}$N reaction. The GT strength is approximately 80% concentrated in the g.s. of ^{18}F, with a relatively small fraction ($\sim$5%) observed in the $T=1$ component. We note that the s-d shell model predictions give a satisfactory description of both the relative strengths and locations of the centroids of the $T=0$ and $T=1$ components of the GT strength. The (p,n) reaction shows that there is not a significantly greater amount of GT strength in the higher-lying states than indicated by the shell-model calculations.

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[1]W. G. Love and M. A. Franey, Phys. Rev. C 24, 1073 (1981).

[2]C. D. Goodman, C. A. Goulding, M. B. Greenfield, J. Rapaport, D. E. Bainum, C. C. Foster, W. G. Love, and F. Petrovich, Phys. Rev. Lett. 44, 1755 (1980).

[3]D. E. Bainum, J. Rapaport, C. D. Goodman, D. J. Horen, C. C. Foster, M. B. Greenfield, and C. A. Goulding, Phys. Rev. Lett. 44, 1751 (1980).

[4]C. Gaarde, J. Rapaport, T. N. Taddeucci, C. D. Goodman, C. C. Foster, D. E. Bainum, C. A. Goulding, M. B. Greenfield, D. J. Horen, and E. Sugarbaker, Nucl. Phys. A369, 258 (1981).

[5]C. D. Goodman, C. C. Foster, D. E. Bainum, S. D. Bloom, C. Gaarde, J. Larsen, C. A. Goulding, D. J. Horen, T. Masterson, S. Grimes, J. Rapaport, T. N. Taddeucci, and E. Sugarbaker, Phys. Lett. 107B, 406 (1981).

[6]C. D. Goodman, C. C. Foster, D. E. Bainum, C. Gaarde, J. Larsen, C. A. Goulding, D. J. Horen, T. Masterson, J. Rapaport, T. N. Taddeucci, and E. Sugarbaker, Bull.

Am. Phys. Soc. 26, 634 (1981).

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

[8]B. D. Anderson, J. N. Knudson, and R. Madey, Nucl. Instrum. Methods 169, 153 (1980).

[9]A. Fazely, B. D. Anderson, M. Ahmad, A. R. Baldwin, A. M. Kalenda, R. J. McCarthy, J. W. Watson, R. Madey, W. Bertozzi, T. N. Buti, J. M. Finn, M. A. Kovash, B. Pugh, and C. C. Foster, Phys. Rev. C 25, 1760 (1982).

[10]F. Ajzenberg-Selove, Nucl. Phys. A392, 1 (1983).

[11]J. W. Olness, E. K. Warbuton, D. E. Alburger, J. C. Lister, and D. J. Millener, Nucl. Phys. A373, 13 (1982).

[12]A. Fazely, R. Madey, B. D. Anderson, A. R. Baldwin, C. Lebo, P. C. Tandy, J. W. Watson, W. Bertozzi, T. N. Buti, M. Finn, C. Hyde, J. Kelly, M. Kovash, B. Pugh, and C. C. Foster (unpublished); A. Fazely, Ph.D. dissertation, Kent State University, 1982 (unpublished).

[13]R. Schaeffer and J. Raynal (unpublished). The modified version of this code was supplied to us by W. G. Love.

[14]J. R. Comfort and B. C. Karp, Phys. Rev. C 21, 2162 (1980).

[15]J. C. Hardy, H. Schmeing, J. S. Geiger, and R. L. Graham, Nucl. Phys. A246, 61 (1975).

[16]H. S. Wilson, R. W. Kavanaugh, and F. M. Mann, Phys. Rev. C 22, 1696 (1980).

[17]C. Gaarde, J. S. Larsen, M. N. Harakeh, S. Y. Van der Werf, M. Igarashi, and A. Müller-Arnke, Nucl. Phys. A334, 248 (1980).

[18]A. Friebel, H.-D. Gräf, W. Gross, W. Knüpfer, G. Küchler, G. Kühner, D. Meuer, S. Müller, A. Richter, E. Spamer, W. Steffen, W. Stock, and O. Titze, Proceedings of the International Conference on Nuclear Physics, Lawrence Berkeley Laboratory Report LBL-11118, 1980, p. 233.

[19]K. A. Snover, in *Polarization Phenomena in Nuclear Physics—1980 (Fifth International Symposium Santa Fe),* Proceedings of the Fifth International Symposium on Polarization Phenomena in Nuclear Physics, AIP Conf. Proc. No. 69, edited by G. G. Ohlsen, R. E. Brown, N. Jarmie, W. W. McNaughton, and G. M. Hale (AIP, New York, 1981), p. 321; K. A. Snover, in *Neutron Capture Gamma Ray Spectroscopy,* edited by R. E. Chrien and W. R. Kane (Plenum, New York, 1979), p. 319; K. A. Snover, P. G. Ikossi, and T. A. Trainor, Phys. Rev. Lett. 43, 117 (1979).

[20]B. H. Wildenthal and W. Chung, in *The (p,n) Reaction and the Nucleon-Nucleon Force,* edited by C. D. Goodman, S. M. Austin, S. D. Bloom, J. Rapaport, and G. R. Satchler (Plenum, New York, 1980), p. 89.

[21]T. T. S. Kuo, Nucl. Phys. A103, 71 (1967).

[22]B. A. Brown, W. Chung, and B. H. Wildenthal, Phys. Rev. Lett. 40, 1631 (1978).

[23]E. C. Halbert, J. B. McGrory, B. H. Wildenthal, and S. P. Pandya, in *Advances in Nuclear Physics,* edited by M. Baranger and E. Vogt (Plenum, New York, 1971), Vol. IV.

[24]J. B. McGrory and B. H. Wildenthal, Phys. Rev. C 7, 974 (1973).