system which is apparently not achieved prior to complete damping.[2,5] Therefore only a portion of the cross section corresponds to this completely damped condition.

Finally we note that this analysis focusses only on the most probable partial waves. While in the classical model there is a correspondence between deflection angle and angular momentum, the experimental width of the energy distributions arises at least in part from the range of partial waves contributing to the observed products. Therefore partial waves even lower than those corresponding to the most probable kinetic energies can be contributing.

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Observation of a $T_>$ Gamow-Teller State in ^{48}Ca$(p,n)^{48}$Sc at 160 MeV

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Neutron spectra from the reaction ^{48}Ca$(p,n)^{48}$Sc at 160 MeV reveal a prominent narrow peak at $E_x = 16.8$ MeV. This state is interpreted as a spin-flip isovector giant resonance; it carries a significant fraction of the $T_>$ $(T=4)$ Gamow-Teller strength. The observed position of this resonance agrees with both a recent shell-model prediction and with the position expected from systematics for the analog of the giant $M1$ resonance in ^{48}Ca.

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Broad peaks observed previously[1-4] in charge-exchange reactions on target nuclei with $N>Z$ were interpreted as carrying a significant amount of Gamow-Teller (spin-flip, isospin-flip) strength. The Gamow-Teller (GT) operator $(\sum_i \tau_i^- \vec{\sigma}_i)$ acting on a target with $N>Z$ can populate states with isospin equal to $(T_>)$ or one less than $(T_<)$ the isospin of the target. (The GT operator can weakly excite states with isospin 1 greater than the isospin of the target.) The $T_<$ component of the GT strength was observed[1-4] via charge-exchange reactions in several nuclei to be broadly distributed near the isobaric analog state (IAS). The $T_>$ component of the GT strength is expected to appear at higher excitation energy. An earlier report[2] of $T_>$ GT strength in the reactions ^{90}Zr$(p,n)^{90}$Nb and ^{90}Zr$(^3$He$,t)^{90}$Nb was reinterpreted[5] as the $T_<$ component of the analog of the giant $E1$ resonance. In this Letter, we present neutron data showing a narrow (<280 keV) state in the reaction ^{48}Ca$(p,n)^{48}$Sc at 160 MeV which we interpret as the $T_>$ $(T=4)$ component of the giant GT resonance in ^{48}Sc or equivalently as the analog of the giant $M1$ resonance in ^{48}Ca.

Neutron energy and angular distributions were measured by the time-of-flight technique at the beam-swinger facility[6] of the Indiana University Cyclotron Facility. An energy resolution of 450 keV for 157-MeV neutrons was achieved with a flight path of 68.0 m. The neutron detector consisted of two large-volume (26.4-l) mean-timed,[7] NE-102 plastic-scintillation counters preceded by an anticoincidence counter. The ^{48}Ca target was enriched to 97.3% with the principal contaminant being (2.6%) ^{40}Ca. The target thickness was 29.3 ± 0.5 mg/cm^2. The proton beam intensity was measured with a well-shielded Faraday cup located approximately 10 m downstream from the target. The detection efficiencies of the neutron counters were calculated with the improved Monte Carlo code of Cecil *et al.*[8,9] The various individual uncertainties combined in quadrature yield an overall scale uncertainty of about ±10%.

The excitation energy scale was set by identifying the sharp neutron peak as the known[10] 1^+ state at $E_x = 2.52$ MeV. The energy calibration was determined from the measured time calibration and the known flight path. The uncertainty in the energy calibration which is dominated by the (±0.2 m) uncertainty in the flight path results in an uncertainty of ±0.05 MeV in the excitation energy of the 16.81-MeV state relative to the 2.52-MeV state. The calibration was checked by verifying that the isobaric analog state (IAS) appeared at its known[10] excitation energy of 6.67 MeV and by observing the location of the ^{12}C(p,n)^{12}N (g.s.) peak with a hydrocarbon-scintillator target. The latter check provides an independent confirmation, good to within the estimated experimental uncertainty of ±50 keV, of both the origin and the calibration of the energy scale. Although the peak seen at $E_x = 16.8$ MeV corresponds to a neutron energy close to those energies expected from the reactions ^{12}C(p,n)^{12}N(g.s.) and ^{16}O(p,n)-^{16}F(g.s.), the energy calibration shows that the neutron energy for the observed peak is more than 800 ± 50 keV higher and lower, respectively, than the neutron energies from these reactions; furthermore, our own earlier measurements[11] between 0° and 10° of ^{12}C(p,n)^{12}N and ^{16}O(p,n)^{16}F neutron spectra at 160 MeV reveal structure clearly not seen in these measurements. The ^{12}C(p,n) spectra at angles greater than about 5° show more than one strongly excited state; whereas the ^{48}Ca(p,n) spectra reveal no such structure near the 16.8-MeV state. (The ^{48}Ca target was stored in vacuum and transferred in an argon atmosphere.)

The state at 16.8 MeV is the most striking feature of the energy spectrum above 12 MeV. The observed width of this state is (20 ± 4)% greater than the observed width of the state at 2.52 MeV. Since the intrinsic energy resolution is negligibly different for these two states, we can determine an upper limit of 280 keV for the width of the 16.8-MeV state by quadratically subtracting the observed width for the 2.52-MeV state. The angular distribution for the 16.8-MeV state is peaked strongly at 0°. Compared in Fig. 1 is the angular distribution for the 16.8-MeV state and that of the known 1^+ state at $E_x = 2.52$ MeV. The dashed lines are microscopic distorted-wave Born-approximation (DWBA) calculations[12] assuming $\Delta L = 0$ angular-momentum transfers. The experimental angular distributions are consistent with the shape of the calculations. We make the tentative assignment $J^\pi = 1^+$ for this 16.8-MeV state.

The required $\Delta S = 1$ spin transfer can be provided by the isovector spin-flip component of the effective interaction, which produces a GT transition. In the simple model of the ground state of ^{48}Ca as a pure $(f_{7/2})^8$ configuration, the GT operator $(\sum_i \tau_i^- \vec{\sigma}_i)$ produces only the two possible configurations $(\pi f_{7/2}, \nu f_{7/2}^{-1})_{1^+}$ and $(\pi f_{5/2}, \nu f_{7/2}^{-1})_{1^+}$. The first configuration can have isospin $T = 3$; the second, both $T = 3$ and $T = 4$. We estimate the excitation energy of the $T = 4$ (or $T_>$) configuration relative to the isobaric analog state (IAS) as follows: The spin-orbit splitting of the f orbital is

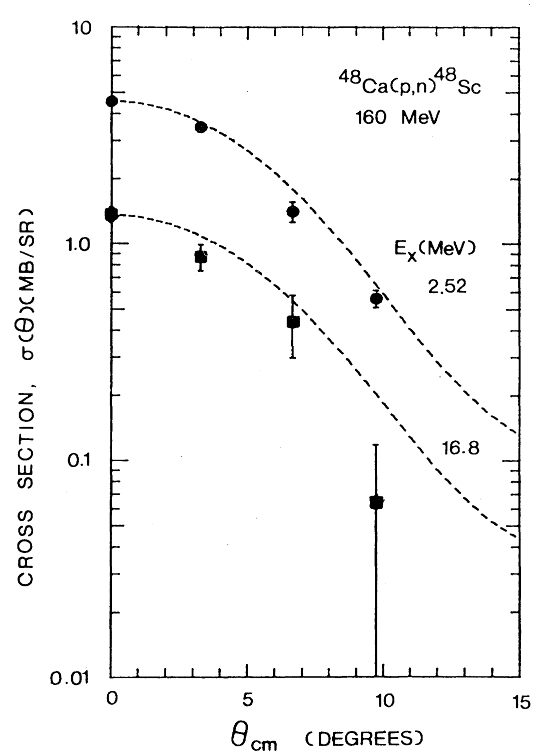

FIG. 1. Angular distributions of the differential cross sections for the sharp states seen at $E_x = 2.52$ and 16.8 MeV. The dashed lines represent DWBA calculations (Ref. 12) with the assumption of $\Delta L = 0$ angular momentum transfers (arbitrarily normalized at forward angles).

about 6 MeV from the known energy levels of the excited states of ^{41}Sc.[13] The main effect of residual interactions should be the pairing-energy term. The need to overcome the pairing energy in promoting an $f_{7/2}$ nucleon from the analog state requires about 4 MeV.[14] Thus, this simple estimate indicates that the excitation energy of the $T=4$ GT state is 10 MeV above the IAS, or at a net excitation energy of about 17 MeV. In the closed-shell model of ^{48}Ca, the giant $M1$ resonance is equivalent to the $(f_{5/2}, f_{7/2}^{-1})_{1^+}$ excitation; an independent estimate from the Fagg[15] systematics for $M1$ excitations (i.e., $40/A^{1/3}$ for $A \geq 40$) yields an excitation energy of 11 MeV in ^{48}Ca or 17.7 MeV in ^{48}Sc. Both these estimates agree well with the 16.8-MeV measurement.

The $T=4$ assignment for the 16.8-MeV state is indicated also by a shell-model calculation of the 1^+ states in ^{48}Sc by Gaarde *et al.*[16] Their calculation assumed the ground state of ^{48}Ca to be pure $(f_{7/2})^8$ and the 1^+ model space to contain all possible states with a single nucleon excited from the $f_{7/2}$ orbit into one of the $2p_{3/2}$, $2p_{1/2}$, or $1f_{5/2}$ orbits, as well as the important $(\pi f_{7/2}, \nu f_{7/2}^{-1})_{1^+}$ state. Their calculation of the 1^+ spectrum produced 19 $T=3$ states at excitation energies from about 2.5 to 14 MeV, and a single $T=4$ state with an excitation energy of 17.2 MeV. Their calculated 1^+ spectrum is compared with the measured (p,n) spectrum in Fig. 2; they agree remarkably well. This shell-model calculation suggests that additional $T=4$ strength would have to come from configurations outside the f-p shell or from more complicated particle-hole excitations which are unlikely if we make the reasonable assumption of

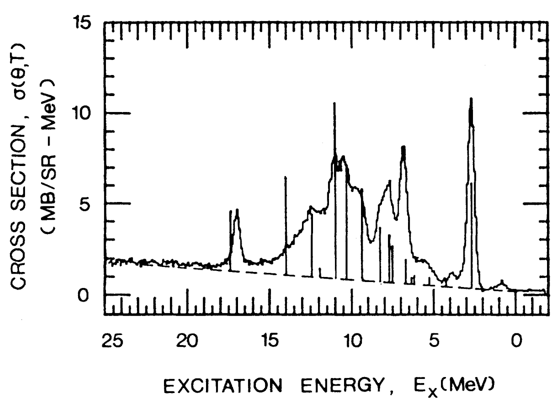

FIG. 2. Neutron energy spectrum for ^{48}Ca$(p,n)^{48}$Sc at $\theta = 0°$ and $T_p = 160$ MeV. The vertical bars indicate the location and relative strengths of 1^+ states predicted by the shell-model calculation of Gaarde *et al.* (Ref. 16).

a one-step reaction mechanism for forward angles); therefore, we expect the $T=4$ state to be narrow.

As shown in Fig. 2, the shell-model calculation by Gaarde *et al.*[16] of the 1^+ spectrum predicts that the $T=3$ strength is distributed broadly in excitation energy from 2.52 to 13.8 MeV. Our measurements in this excitation energy region reveal that the strongly excited strength is forward peaked, and that the observed 19 to 1 ratio of the $T=3$ to the $T=4$ GT strength is similar to the 13 to 1 ratio expected by applying the GT operator to a pure $(f_{7/2})^8$ ^{48}Ca ground state.[17] Also, the (p,n) spectrum is similar to the ^{48}Ca(^{3}He, t)^{48}Sc spectrum of Gaarde *et al.*[16] at 66 MeV. Gaarde *et al.* see the 2.52-MeV, 1^+ state and the IAS strongly excited, and they see a broad distribution of strongly excited, forward-peaked states with excitation energies between 5 and 14 MeV, which they interpret as $T=3$ GT strength. Because of problems with target contamination, they were unable to reliably identify any states in ^{48}Sc near the 16.8-MeV state reported here. Also, the lower (22-MeV/A) beam energy of their experiment inhibits the excitation of the GT states relative to other processes.

At medium energies, the 0° (p,n) cross sections are proportional to the squares of the Fermi (F) or GT matrix elements for the nuclear transition, and also to the squares of the volume integrals of the corresponding isovector terms of the nucleon-nucleon effective interaction.[18] This relationship permits a determination of the fraction of the GT sum-rule strength observed in the present measurements. The Gamow-Teller strength[16] $\mathfrak{M}_{GT}^2 = |\langle 1^+|\sum_i \tau_i^- \vec{\sigma}_i|\text{g.s.}\rangle|^2 = 3(N-Z)$; the Fermi strength $\mathfrak{M}_F^2 = |\langle \text{IAS}|\sum_i \tau_i^-|\text{g.s.}\rangle|^2 = N-Z$. Based on the estimate[18] that distortion effects are approximately 30% stronger for Fermi-type transitions than for GT-type transitions, the net GT cross section will be enhanced over the IAS cross section by about $1.3\,(\mathfrak{M}_{GT}/\mathfrak{M}_F)^2 (J_{\sigma\tau}/J_\tau)^2 \approx 4(J_{\sigma\tau}/J_\tau)^2$, where $J_{\sigma\tau}$ and J_τ are the volume integrals mentioned above. From the 160-MeV interaction tabulated by Love,[19] we obtain $(J_{\sigma\tau}/J_\tau)^2 \simeq 5$, and find that the net ratio of GT to F strength should be about 20. As mentioned above, we take the GT strength to be split in $T_>$ and $T_<$ components in the ratio 13:1. Thus, the $T_>$ and $T_<$ GT strengths should be 20(1/14) and 20(13/14) times the Fermi strength, respectively. We assume the Fermi strength is concentrated entirely in the IAS. From our 0° cross sections [viz., 3.81, 1.56, and 29.1 mb/sr for the IAS, the 16.8-

MeV state, and the strength between 2.5 and 14 MeV (not including the IAS), respectively], we find that the 16.8-MeV state exhausts 29% of the sum rule for $T_>$ GT strength; and that the 1^+ states seen at lower excitation energies exhaust about 41% of the sum rule for $T_<$ GT strength. These results for the sum-rule strengths are estimated to be accurate to about 30%. Note that the fractions of the sum-rule strengths seen here are similar to the reduced $M1$ strengths reported[20] previously for medium- and heavy-weight nuclei and indicate that the quenching of $M1$ strength could be a characteristic feature of the structure of such nuclei.

In conclusion, we observed a narrow state at an excitation energy of 16.8 MeV in ^{48}Sc via the ^{48}Ca(p,n) reaction at 160 MeV which we interpret as the $T_>$ GT state for this reaction. The state is observed at an excitation energy consistent with both a simple estimate for the location of the $T_>$ strength and a shell-model calculation of 1^+ strength in ^{48}Sc. The 16.8-MeV state carries approximately 30% of the expected $T_>$ strength similar to the fraction of the total GT strength seen in $T_<$, 1^+ states at lower excitation energies. We attribute the narrowness of the state to the fact that the $T_>$ GT strength is expected to be concentrated in a single-particle, single-hole shell-model configuration for a closed-shell model of ^{48}Ca.

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