Observation of $T=1$ and $T=0$ Gamow-Teller States in the Reaction ^{54}Fe(p,n)^{54}Co

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The reaction ^{54}Fe(p,n)^{54}Co has been studied at $E_p = 32$, 35, and 40 MeV. Two prominent peaks observed at $E_x = 5.32$ and 10.23 MeV are assigned as 1^+ from the energy dependence of cross sections and the angular distribution measurements, and interpreted as the $T=0$ and $T=1$ components of the Gamow-Teller giant resonance. They carry 40–50% of the expected strengths. The energies and strengths of these peaks agree with a recent shell-model calculation.

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Spin-isospin modes of nuclear excitation and their relation to the π- and ρ-meson exchange interactions[1] in finite nuclear systems are arousing increasing interest, and have advanced a new approach to the understanding of nuclei as systems of elementary particles. Such excitation modes are currently extensively studied in a variety of experiments. Charge-exchange reactions can excite states carrying a significant fraction of the Gamow-Teller (GT) strength, especially those which are energetically inaccessible in β decays, and are thus hoped to supplement other experiments with independent information.

In recent (p,n) studies GT states in $N>Z$ nuclei have been observed in many nuclei.[2-7] Furthermore a close relationship has been established[8,9] between the GT β-decay strength and (p,n) cross sections. The GT strength extracted from the (p,n) data is subject to the choice of the effective interaction and other assumptions involved. Nevertheless it seems well established[8] that the observed GT strength is usually 30–50% of the sum-rule limit. The "missing" GT strength presents a challenging problem to nuclear theories, and explanations in terms of core polarization,[10] mesonic effects,[1,11] Δ excitation,[12,13] etc., have been explored.

So far both the $T_<$ and the $T_>$ GT states in $N>Z$ nuclei are observed only in ^{48}Sc, ^{90}Nb, and ^{208}Bi. In ^{90}Nb and ^{208}Bi the GT states have widths of 1–4 MeV.[3,5] Although such concentrations have been predicted,[14] they are much narrower than simple expectations,[15] and await further calculations. The width of the $T_>$ GT state in ^{48}Sc is found to be less than 280 keV,[4] and because of their narrow widths the $T=4$ GT states in ^{48}Sc and ^{48}Ca are thought to be a good place to study precritical phenomena of pion condensation.[16] On the other hand the $T_<$ GT state in ^{48}Sc is largely fragmented, making a comparison with the sum rule somewhat difficult. Such fragmentation was qualitatively explained by the two-particle–two-hole admixtures.[17] Gaarde *et al.* have recently studied[18] the (^{3}He, t) reaction on ^{54}Fe. Both the $T_<$ and $T_>$ GT strengths are expected to be concentrated in the residual ^{54}Co nucleus.[18] However, the complicated reaction processes involved[17,18] seem to make it difficult to identify GT states in (^{3}He, t) reactions.

We have studied the ^{54}Fe(p,n)^{54}Co reaction at $E_p = 32$, 35, and 40 MeV, and observed two prominent narrow peaks at $E_x = 5.32$ and 10.23 MeV. We tentatively assign these to be the $T = 0$ and $T = 1$ GT states in ^{54}Co. A comparison of their cross sections with those for the low-lying 0^+ and 1^+ states enabled us to extract GT strengths.

The experiment was performed with use of proton beams from the azimuthally varying field cyclotron and the time-of-flight facilities at the Cyclotron and Radioisotope Center, Tohoku University. We have utilized a beam swinger system, and measured angular distributions of emitted neutrons between 0° and 90° at $E_p = 35$ MeV. Neutron spectra have also been taken at several angles at $E_p = 32$ and 40 MeV. Details of the time-of-flight facilities have been published elsewhere.[19] Two targets were prepared by rolling metallic iron, enriched to 97.6% in ^{54}Fe. Their thicknesses were 1.4 and 6.1 mg/cm^2. Overall time resolution was 1.3 ns. The detector efficiencies were calibrated at several energies by using the known (p,n) cross sections[20] on ^{7}Li and found to be in good agreement with a Monte Carlo calculation. The errors in the absolute magnitude of the cross sections are estimated to be ~20%, while the relative errors are ~7%.

A representative neutron energy spectrum is shown in Fig. 1. In addition to the ground state, which is the isobaric analog state (IAS) of the ground state of ^{54}Fe, and the known states at 0.20 MeV ($7^+, T = 0$), 0.94 MeV ($1^+, T = 0$), and 1.45 MeV ($2^+, T = 1$), several other states are seen to be excited. The distribution of GT strengths predicted by the shell-model calculation of Gaarde *et al.*[18] is shown in the upper part of Fig. 1. A comparison in Fig. 1 readily suggests that the peaks at 5.32 and 10.23 MeV may correspond to the calculated $T_<$ and $T_>$ GT states. The intensities of these peaks, as well as that of the 0.94-MeV peak, increase with increasing incident energy. The ratios of the cross sections $I(E_p = 40\ \text{MeV})/I(E_p = 35\ \text{MeV})/I(E_p = 32\ \text{MeV})$ integrated between 3° and 40° are 1/0.82/0.72, 1/0.81/0.78,

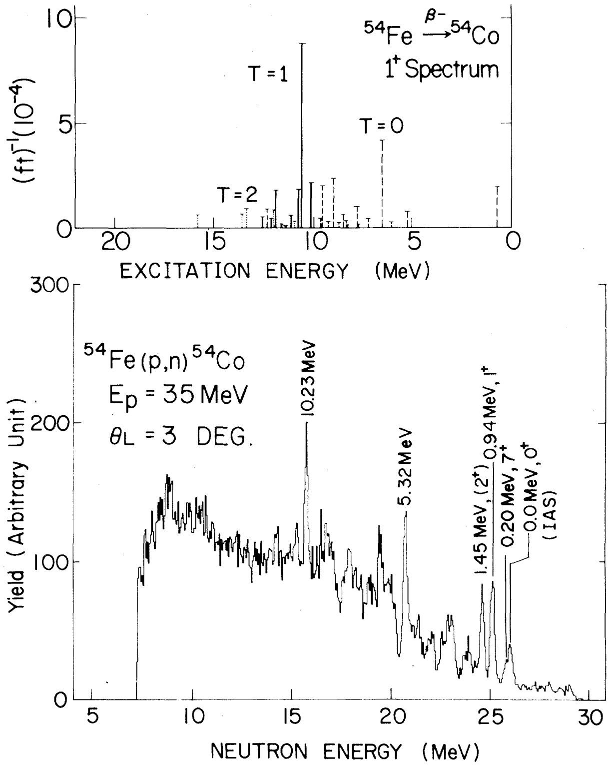

FIG. 1. Neutron energy spectrum for the reaction ^{54}Fe$(p,n)^{54}$Co at $\theta_{\text{lab}} = 3°$ measured with 35-MeV protons at a neutron flight path of 24.6 m. Energy per bin is 50 keV. Also shown is the theoretical prediction for the locations and strengths of 1^+ states by Gaarde *et al.* (Ref. 18).

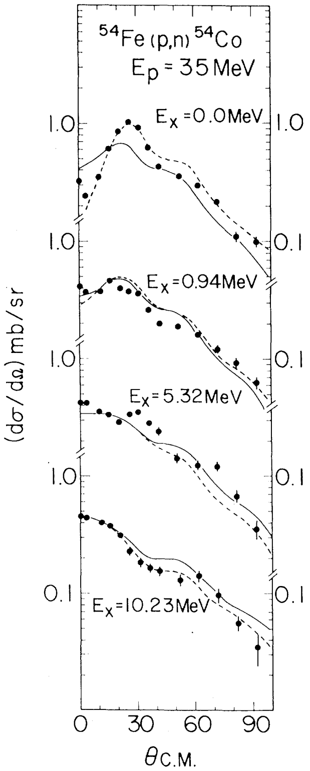

FIG. 2. Differential cross sections for the peaks corresponding to the IAS and the 0.94–, 5.32–, 10.23–MeV states in ^{54}Co. The curves are DWBA predictions calculated with 1.0-fm-range Yukawa forces (solid) and with M3Y (dashed). The solid curves for the 5.32- and 10.23-MeV states and the dashed curves are normalized to the data at $\theta_{\text{c.m.}} = 15.1°$.

and 1/0.80/0.58 for the 0.94-, 5.32-, and 10.23-MeV peaks, whereas it is 1/1.08/1.07 for the IAS. Such behavior is consistent[8] with the 1^+ assignments to the 5.32- and 10.23-MeV states. We estimate the width of the 5.32-MeV state to be $\lesssim 80$ keV and that of the 10.23-MeV state to be 95 ± 30 keV by quadratically subtracting the contributions of time spread and the target thickness from the observed peak widths.

Figure 2 shows the angular distributions for the IAS and the 0.94-, 5.32-, and 10.23-MeV states at $E_p=35$ MeV. Solid curves in Fig. 2 are distorted-wave Born-approximation (DWBA) predictions calculated by the code DWBA-70, which includes knock-on exchange contributions.[21] The effective interaction for the reaction has been taken to be the phenomenological nucleon-nucleon force[22] with a 1.0-fm Yukawa radial dependence and $V_0=27$ MeV, $V_\sigma=V_{\sigma\tau}=12$ MeV, and $V_\tau=18$ MeV. This interaction has been successfully used[23] in the analyses of many (p,n) analog transitions between $E_p=25$ and 45 MeV. Optical-potential parameters of Becchetti and Greenlees[24] (BG) are used for protons. Those for neutrons are self-consistent potential parameters derived by Carlson, Zafiratos, and Lind[25] from the BG potentials. Pure $(\pi f_{7/2}{}^6\nu f_{7/2}{}^8)$ and $(\pi f_{7/2}{}^7\nu f_{7/2}{}^7)$ configurations are assumed for the ground state of ^{54}Fe and for the ground state (0^+) and the 0.94-MeV state (1^+) of ^{54}Co, respectively. The DWBA curves for the 5.32- and 10.23-MeV states are calculated for the pure $(\pi f_{5/2}\pi f_{7/2}{}^6\nu f_{7/2}{}^7)_{1^+}$ configuration. The DWBA calculations reproduce very well not only the angular distribution shapes but also the magnitudes of the cross sections for the ground state and the 0.94-MeV state. The calculated angular distribution shapes for the 5.32- and 10.23-MeV states are also in good agreement with the measurements, supporting the 1^+ assignments to those states. The DWBA calculations with the effective interaction of Bertsch *et al.*[26] (M3Y) give a somewhat better account of the measured angular distribution shapes (dashed curves), but underestimate the 0^+ cross section for the IAS by a factor of 2 and overestimate the 1^+ cross section for the 0.94-MeV state by 50%. Similar difficulties with the M3Y interaction have been reported in previous analyses.[8,27]

The (p,n) cross sections for these states may be compared with the β-decay matrix elements. In the present experiment the momentum transfer q, 0.12 fm^{-1} for the IAS and 0.20 fm^{-1} for the 10.23-MeV state at 15.2°, is small enough to allow such a comparison. Also the effects of tensor and *LS* terms in the effective interaction are expected to be small for such small q, and indeed DWBA calculations corroborate such a presumption. The effects of distortion and exchange knock-out contributions are taken care of in the DWBA calculations, and the following arguments are subject only to the strengths $V_{\sigma\tau}$ and V_τ in the assumed effective interaction.

The logft value of the $^{54}\mathrm{Co}(0^+)\to{}^{54}\mathrm{Fe}(0^+)$ β decay is known to be 3.5. This value is almost identical to 3.49, which is expected for the pure $(\pi f_{7/2}{}^7\nu f_{7/2}{}^7)_{01}\to(\pi f_{7/2}{}^6\nu f_{7/2}{}^8)_{01}$ transition. The 0.94-MeV state is usually thought to be of the pure $(\pi f_{7/2}{}^7\nu f_{7/2}{}^7)$ configuration. Indeed 100% of the observed (p,n) strengths for the IAS and the 0.94 state are explained by the DWBA calculation in the present analysis. The measured cross section of the 10.23-MeV state is about 40% of the calculated total $T_>$ GT strength, and that for the 5.32-MeV state about 50% of the $T_<$ GT strength calculated for the $(\pi f_{5/2}\pi f_{7/2}{}^6\nu f_{7/2}{}^7)$ configuration. The shell-model calculation of Gaarde *et al.*[18] predicts a $T=1$ 1^+ state at 10.7 MeV in ^{54}Co with a GT strength of $(ft)^{-1}=8.8\times10^{-4}$, or about 50% of the total $T_>$ GT strength. A $T=0$ 1^+ state is also predicted in their calculation at about 6.7 MeV, with a $T_<$ GT strength of $(ft)^{-1}=4.2\times10^{-4}$, or about 32% of the $\nu f_{7/2}\to\pi f_{5/2}$ $T_<$ GT strength. These numbers are in qualitative agreement with the present result; in other words core polarization seems to explain the observed (p,n) strength.

In conclusion, we observed states at excitation energies of 5.32 and 10.23 MeV in the reaction $^{54}\mathrm{Fe}(p,n)^{54}\mathrm{Co}$. Their widths are $\lesssim 80$ and 95 ± 30 keV, respectively. The incident energy dependence of cross-section ratios and the angular distributions strongly suggest 1^+ assignments to these states. We interpret them as the $T=0$ and $T=1$ 1^+ states, which carry 40–50% of the expected GT strengths. The energies and the strengths of these states seem to be explained within the framework of a conventional shell-model calculation.

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Forward- and Backward-Angle Differential Cross Section for Neutron-Proton Capture at 72 MeV

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The neutron-proton capture differential cross section has been measured at extreme forward and backward angles for 72-MeV neutron energy corresponding to a γ-ray energy of 38.2 MeV in the inverse reaction. The results agree well with recent photodisintegration data at forward angles, but only partially with potential model calculations.

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A basic process in the nucleon-nucleon (N-N) field, the deuteron photodisintegration, has recently received much attention, from both the experimental and the theoretical sides. A measurement by Hughes *et al.*[1] of the 0° differential cross section in the γ-ray energy range 20–120 MeV was found to be in disagreement with the Partovi[2] calculation which, it is believed, should be accurate within a few percent if conventional ideas about the two-nucleon interaction are at all correct. A series of calculations were initiated by this discrepancy. Lomon[3] found a moderate sensitivity to the D-state percentage of the deuteron, with a Hamada-Johnston or Feshbach-Lomon N-N interaction. Rustgi, Sandhu, and Rustgi,[4] using supersoft core potentials, somewhat reduced the discrepancy with the data of Hughes *et al.* Arenhövel and Fabian[5] checked the influence of the tensor force in a Holinde-Machleidt potential. Finally, a modification of Siegert's theorem as well as new constraints on the N-N interaction at short distance were discussed.[6] No calculation was really able to reproduce the data of Hughes *et al.* An extensive reference list for this problem can be found in a recent review paper.[7]