Observation of Analog and Nonanalog Transitions in the Reaction $^{56}Fe(\pi^+, \pi^-)^{56}Ni$

Peter A. Seidl, Rex R. Kiziah, Mark K. Brown, and C. Fred Moore
University of Texas at Austin, Austin, Texas 78712

and

C. L. Morris and Helmut Baer
Los Alamos National Laboratory, Los Alamos, New Mexico 87545

and

Steven J. Greene, G. R. Burleson, and W. B. Cottingame
New Mexico State University, Las Cruces, New Mexico 88003

and

L. C. Bland and R. Gilman
University of Pennsylvania, Philadelphia, Pennsylvania 19104

and

H. T. Fortune[(a)]
Los Alamos National Laboratory, Los Alamos, New Mexico 87545, and University of Pennsylvania, Philadelphia, Pennsylvania 19104

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An excitation function for the reaction $^{56}Fe(\pi^+,\pi^-)^{56}Ni$ has been measured at $\theta_{\rm lab} = 5°$ for incident pion energies of 140–290 MeV. The transition to the lowest-lying $T = 0$ state is similar to previous observations, but that to the lowest-lying $T=2$ state is not, except in the high-energy range.

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There is evidence for two dramatically different reaction mechanisms in pion-induced double-charge-exchange (DCX) reactions. Current published theoretical calculations deal with only one of these mechanisms, double-isobaric-analog transitions (DIAT).[1,2] Previous measurements have shown that nonanalog transitions, which change T by two units, have relatively large cross sections and that their global characteristics[3] (energy dependence[4] and dependence on target mass,[5] discussed below) are different from those for DIAT. This communication reports the observation of the energy dependence of both double-analog and nonanalog DCX transitions on the same target nucleus, in the reaction $^{56}Fe(\pi^+, \pi^-)^{56}Ni$. Earlier comparisons were between analog and nonanalog transitions on different target nuclei.

The double-isobaric-analog state (DIAS) of the ^{56}Fe ground state is not the ground state of ^{56}Ni. Previous measurements of $^{58}Ni(p, t)^{56}Ni$ (Ref. 6) and $^{54}Fe(^3He, n)^{56}Ni$ (Ref. 7) are not in good agreement as to the location of the DIAS in ^{56}Ni, but generally find the state at $E_x \simeq 9.9$ MeV. As was reported earlier by Morris *et al.*,[8] pion-induced DCX makes possible the selective excitation of the DIAS in heavy nuclei even when the state is in a region having a relatively large level density in the residual nucleus. The transition to ^{56}Ni(g.s.) does not suffer from the same identification problem as the DIAS since it is well separated from the first excited state of ^{56}Ni.

The reaction $^{56}Fe(\pi^+, \pi^-)^{56}Ni$ was performed at the Energetic Pion Channel and Spectrometer (EPICS) of the Clinton P. Anderson Meson Physics Facility (LAMPF). The target was natural Fe having an areal density of 2.3 gm/cm^2. Measurements were made at a laboratory angle of 5° with the DCX modification to the EPICS spectrometer, which has been discussed in detail elsewhere.[9] Spectra were accumulated at five incident pion energies, $T_\pi = 140$, 164, 220, 260, and 292 MeV. Normalization of the $^{56}Fe(\pi^+, \pi^-)$-^{56}Ni cross sections was accomplished by measuring relative yields for $^1H(\pi^+, \pi^+)^1H$ at all five energies at a laboratory angle of 50° with a CH_2 target of areal density 73.5 mg/cm^2. Absolute normalization factors were determined by comparing these yields with cross sections calculated from the π-p phase shifts of Rowe, Salomon, and Landau.[10] These energy-dependent absolute normalization factors are accurate within ±20%.

The spectrum comparison of Fig. 1 exhibits the difference in the energy dependence of the nonanalog transition [to ^{56}Ni(g.s.)] and the DIAT at $E_x \simeq 9.6$ MeV. At lower energies, the excitation of ^{56}Ni(g.s.) is clearly seen whereas there are no ground-state events at $T_\pi = 292$ MeV. The spectrum at $T_\pi = 292$ MeV is dominated by the DIAS whereas at $T_\pi = 140$ MeV no clear signal appears for this state.

Figure 2 compares the excitation functions of the analog and nonanalog transitions in ^{56}Ni. From $T_\pi = 140$ to 260 MeV, the DIAT cross section increases monotonically with increasing pion energy—in good agreement with the results of microscopic calculations of Miller[11] for other double-analog transitions. However, this behavior differs at the lower energies from that previously observed for DIAT. The excitation function for the nonanalog transition decreases with increasing pion energy, resulting in only upper limits on the cross sections at the highest energies. The rapid increase of the cross section at the lower energies is similar to previously measured excitation functions[3] for the reactions ^{16}O(π^+, π^-)^{16}Ne(g.s.) and ^{24}Mg(π^+, π^-)^{24}Si(g.s.) where only nonanalog transitions are allowed. The ^{56}Fe(π^+, π^-)^{56}Ni(g.s.) and ^{24}Mg(π^+, π^-)^{24}Si(g.s.) cross sections increase to the lowest pion energy ($T_\pi = 140$ MeV); the ^{16}O(π^+, π^-)^{16}Ne(g.s.) excitation function is peaked around 160 MeV.

Double-analog and nonanalog DCX transitions also have different dependences of cross section on target mass. The geometric model of Johnson[2] predicts that

$$\sigma_{\rm DIAT} \propto (N-Z)(N-Z-1)A^{-10/3}.$$

Greene *et al.*[3] found the unexpected result that this simple expression works well at $T_\pi = 292$ MeV, but they presented only three data points. Figure 3 includes the points published by Greene *et al.*,[3] the results of the present experiment, points for ^{42}Ca(π^+, π^-)^{42}Ti(g.s.) at $T_\pi = 292$ MeV, as reported by Miller,[11] and ^{14}C(π^+, π^-)^{14}O(g.s.), recently measured by Seidl *et al.*[12] The data agree well with an $A^{-10/3}$ mass dependence.

The A dependence of DIAT at $T_\pi = 164$ MeV does not show the simple behavior observed at $T_\pi = 292$ MeV (see Fig. 3). One possible explana-

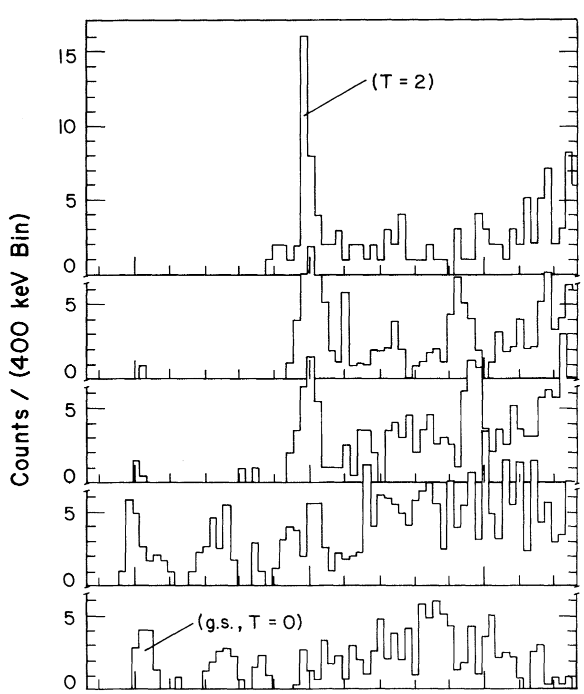

FIG. 1. Comparison of spectra for the reaction ^{56}Fe(π^+,π^-)^{56}Ni at T_π = 140, 164, 220, 260, and 292 MeV (from bottom to top).

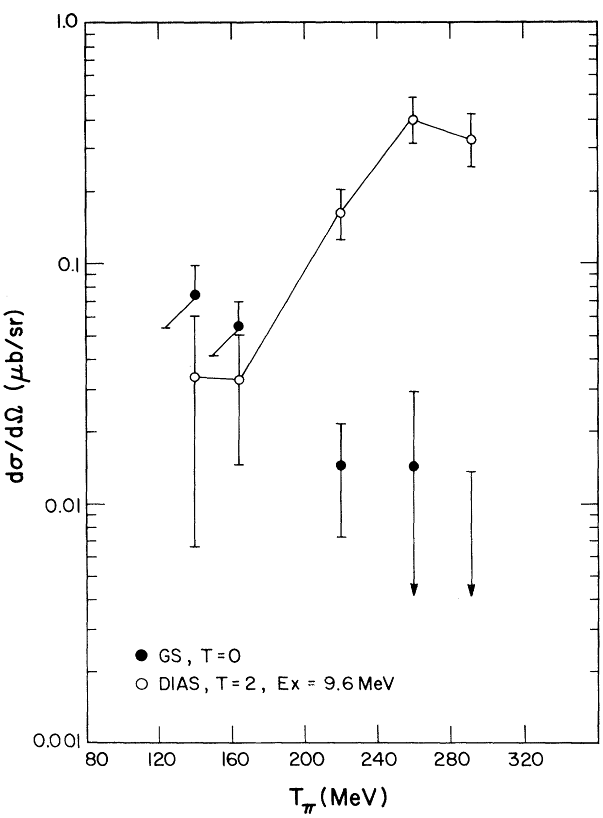

FIG. 2. Comparison of the excitation functions for the ^{56}Ni double-isobaric-analog state ($E_x \simeq 9.6$ MeV) and the nonanalog ^{56}Ni ground state. The solid line through the former serves to guide the eye.

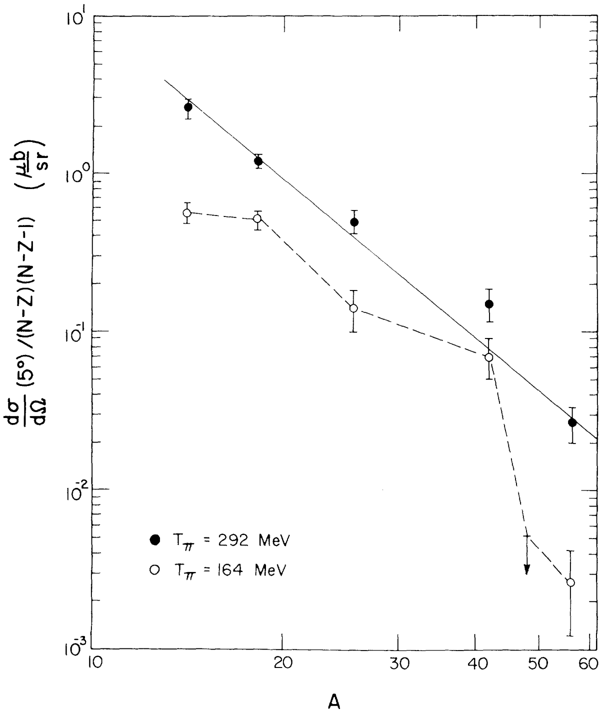

FIG. 3. A dependence of DIAT at $\theta = 5°$. The solid circles are at T_π=292 MeV [^{14}C measured by Seidl *et al.* (Ref. 12), ^{18}O and ^{26}Mg measured by Green *et al.* (Ref. 3), and ^{42}Ca reported by Miller (Ref. 11)]. The open circles are at T_π = 164 MeV [^{14}C measured by Seidl *et al.* (Ref. 12), ^{18}O and ^{26}Mg measured by Greene *et al.* (Ref. 3), and ^{42}Ca and ^{48}Ca reported by Seth (Ref. 13)]. The solid line represents an $A^{-10/3}$ mass dependence. The dashed line serves to guide the eye.

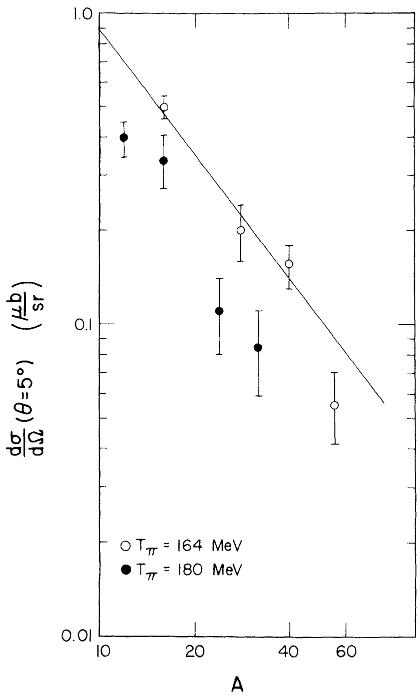

FIG. 4. A dependence of nonanalog DCX transitions. The solid line represents an $A^{-4/3}$ mass dependence.

tion of this lack of regularity is interference[14] between a nonanalog amplitude and the analog amplitude, both of which can contribute to DIAT. Such interference effects may be responsible for the structure of the excitation function[14] near T_π = 164 MeV and are observed in the angular distribution at that energy[15] for the $^{18}O(\pi^+, \pi^-)$-^{18}Ne(g.s.) double-analog transition.

For nonanalog transitions, Morris *et al.*[5] have shown indications for a target mass dependence of $A^{-4/3}$ for DCX on self-conjugate nuclei. One argument for this dependence involves the interpretation of the nonanalog DCX amplitude in terms of excitation of "Δ-hole" components in the final-state wave function by a single-step reaction. Figure 4 compares our present results for $^{56}Fe(\pi^+, \pi^-)^{56}Ni$(g.s.) cross section at $T_\pi = 164$ MeV with those for $T = 0$ to $T = 2$ transitions. The nonanalog transition to ^{56}Ni(g.s.) agrees well with an $A^{-4/3}$ trend.

In summary, new measurements of the $^{56}Fe(\pi^+, \pi^-)^{56}Ni$ reaction continue to confirm that pion-induced DCX cross sections have different energy dependence and A dependence for double-analog states and nonanalog states. The analog cross sections appear to increase smoothly with pion energy and to dominate at higher energies. The nonanalog cross sections are large near $T_\pi = 140$ -160 MeV and negligible at the higher energies. At $T_\pi = 292$ MeV, the analog cross sections are characterized by an $A^{-10/3}$ mass dependence. At energies near $T_\pi = 160$ MeV, the nonanalog cross sections are characterized by an $A^{-4/3}$ mass dependence. The anomalous A dependence of analog cross sections at $T_\pi = 164$ MeV is probably due to an interference between analog and nonanalog amplitudes.

These $^{56}Fe(\pi^+, \pi^-)^{56}Ni$ measurements are the first reported observations of the energy dependence of DIAT and nonanalog transitions in the same nucleus. The importance of these observations is that they remove any possible entrance-channel effects since both analog and nonanalog transitions are observed simultaneously. The cross section for the transition to ^{56}Ni(g.s.) is consistent with the $A^{-4/3}$ mass dependence for nonanalog transitions. Its energy dependence is similar to previously observed nonanalog transitions. The DIAT has an $A^{-10/3}$ mass dependence at 292 MeV, but the excitation function does not exhibit the structure seen in the $^{18}O(\pi^+, \pi^-)^{18}Ne$ and $^{26}Mg(\pi^+, \pi^-)^{26}Si$ double-isobaric-analog transitions.

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[a]Permanent address: University of Pennsylvania, Philadelphia, Pa. 19104.

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