Nonanalog (π^-,π^+) double charge exchange on ^{18}O

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(Received 20 April 1984)

We present measurements of the nonanalog pion double charge exchange reaction, $^{18}O(\pi^-,\pi^+)^{18}C$(g.s.), a transition between a $T=1$ state and a $T=3$ state, and compare the results to earlier measurements on self-conjugate targets.

In the simplest models of pion double charge exchange (DCX), transitions to the analog state in the residual nucleus are expected to dominate the reaction because of the large overlap of the initial- and final-state wave functions. Yet, at energies near the $\Delta_{3,3}$ resonance, it has been found that cross sections to certain nonanalog states are about as large as the analog cross sections.[1,2] In particular, a large body of data exists for transitions between $J^\pi,T=0^+,0$ target ground states and $J^\pi,T=0^+,2$ residual ground states. The regular characteristic features[3] of these transitions ($A^{-4/3}$ mass dependence, diffractive angular distributions, and excitation functions that are peaked near the $\Delta_{3,3}$ resonance) are in sharp contrast to the irregular features of analog DCX transitions (irregular $A^{-10/3}$ mass dependence at 164 MeV, nondiffractive angular distributions, and excitation functions that either monotonically increase across the $\Delta_{3,3}$ resonance, or that have a minimum near $T_\pi=164$ MeV).

No theory exists for nonanalog DCX. Published speculation[4,5] has centered on a model in which a single-step reaction leads to $\Delta_{3,3}$ components of the residual nuclear wave function. If this, or some other exotic reaction mechanism,[6] is responsible for nonanalog DCX on self-conjugate targets, similar transitions should be seen on $T\neq0$ targets. There is, however, no unambiguous evidence of nonanalog DCX transitions on other than $T=0$ targets that have all the features found in DCX on $T=0$ targets. Transitions with some, but not all, of the characteristic features have been seen on targets of ^{9}Be (Ref. 7), ^{13}C (Ref. 8), ^{14}C (Ref. 9), and ^{56}Fe (Ref. 12). Also, the observed anomalies in $^{18}O(\pi^+,\pi^-)^{18}Ne$(g.s.) (Ref. 2) can be explained by the interference of analog and nonanalog amplitudes[10] (or alternatively by a second order calculation[11] including core excitation).

As self-conjugate targets are a special class of nuclei, nonanalog DCX on these targets may exhibit systematic features that are not generally characteristic of the reaction. In particular, we note that the experimental A dependence of nonanalog DCX on self-conjugate targets, $\sigma\sim A^{-4/3}$, disagrees with the $A^{-10/3}$ mass dependence expected for any DCX diagram. The best-fit A dependence[3,5] is

$$\sigma(5^\circ,\ 164\ \text{MeV})\simeq21.06A^{-1.354}\ (\mu\text{b/sr})\ .$$

Constraining the mass dependence to be $A^{-10/3}$ increases the χ^2 per point from ~1 to ~40. Thus, it became of interest to unambiguously demonstrate the existence (or nonexistence) of the systematic features of nonanalog DCX on other than a self-conjugate target, and to examine the mass dependence of the reaction. To ensure the absence of the analog amplitude, but to still connect ground states, the fact that stable nuclei have $N>Z$ requires [unless T (target)$=2$, as in ^{56}Fe] the use of the (π^-,π^+) reaction. We have investigated the reaction $^{18}O(\pi^-,\pi^+)^{18}C$(g.s.), which has quantum numbers

$$J_i^\pi,T(J_f^\pi,T)=0^+,1(0^+,3)\ .$$

This reaction has been used to measure the mass excess of ^{18}C (but a cross section was not measured[13]).

Data were obtained with the standard DCX modification[14] of the EPICS spectrometer at the Clinton P. Anderson Meson Physics Facility (LAMPF). The ^{18}O target was 0.94 g/cm^2 H_2O, of which 94% (by number of molecules) was $H_2{}^{18}O$. The water was frozen in a copper frame with copper entrance and exit windows, and was wrapped with aluminized Mylar for insulation. Because the Q values for DCX on ^{63}Cu (-4.85 MeV), ^{65}Cu (-9.11 MeV), aluminum (-12.59 MeV), ^{12}C (-25.97 MeV), and ^{16}O (-19.45 MeV) are more positive than the Q value for $^{18}O(\pi^-,\pi^+)^{18}C$(g.s.) ($-26.70$ MeV), the spectra include some background at more positive Q values than that corresponding to the ^{18}C(g.s.) peak.

Absolute normalizations of the cross sections were determined by measuring $^1H(\pi^-,\pi^-)$ yields with a CH_2 target at $\theta=40^\circ$ and at all energies at which data were taken. The ratio of yield to cross section, calculated from the phase shifts of Rowe, Salomon, and Landau,[15] gives a normalization factor that compensates for the solid angle of the spectrometer and the flux of pions in the incident beam. Two additional checks of the absolute normalization were made. First, hydrogen yields were measured with the H_2O target. This gives a ratio of the H_2O target thickness to a CH_2 target whose thickness is more accurately determined. The resulting H_2O thickness, 0.91 ± 0.07 g/cm^2, agrees well with the physically measured thickness given above. Second, a measurement was made of ^{18}O$(\pi^+,\pi^-)^{18}$Ne(g.s.) at $\theta=5°$ and $T_\pi=292$ MeV to check our absolute normalization against that of Greene *et al.*[2] Our measurement yielded $\sigma=2.14\pm0.15$ μb/sr, which is slightly less than their value of $\sigma=2.41\pm0.19$ μb/sr, but agrees within the uncertainties.

In addition, as a check on any angle-dependent effects, yields were measured for ^{1}H(π^+,π^+) as a function of angle, and compared with cross sections calculated from phase shifts as above. No statistically significant effects were found except for a 10% increase in the ratio of hydrogen cross section to measured yield at the largest angle, $\theta=45°$. It is believed that this effect was caused by part of the pion beam striking the bellows that vacuum couples the scattering chamber to the beam channel. The $\theta=45°$ ^{18}O data point has been renormalized.

The spectrum shown in Fig. 1 is the sum of all raw ^{18}O(π^-,π^+) spectra at all energies and angles. It has not been corrected for either the acceptance of the spectrometer or the relative normalizations of the data acquisition runs at various angles and energies. There are clear signals (above an irregular background) for both the ground state and an excited state at $E_x=1.55$ MeV. We note that most shell model calculations give the excitation energy of the first 2^+ state as 1.8 MeV $<E_x<2.1$ MeV, and that, in weak coupling, where ^{18}C$=^{20}$O$\otimes^{14}$C, the excitation energy of ^{18}C(2^+) would be the same as ^{20}O(2^+), 1.67 MeV. Background subtraction has been done for the ground state cross sections presented, although the estimated number of background counts in the ground state peak in all spectra (133 total counts at all energies and angles) is only ten counts.

The $\theta=5°$, ^{18}O$(\pi^-,\pi^+)^{18}$C(g.s.) excitation function is compared in Fig. 2 to those for the previously measured[2]

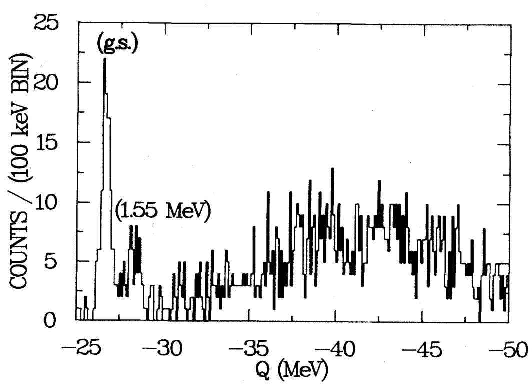

FIG. 1. Sum of all raw ^{18}O(π^-,π^+) spectra at all energies and angles.

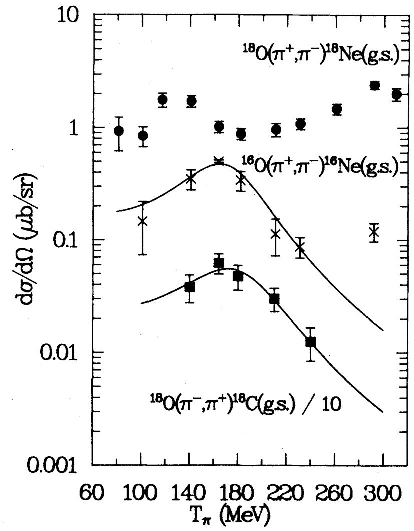

FIG. 2. Excitation function for ^{18}O$(\pi^-,\pi^+)^{18}$C(g.s.) at $\theta=5°$ (lab) contrasted with previously measured excitation functions for ^{16,18}O$(\pi^+,\pi^-)^{16,18}$Ne(g.s.) (Ref. 2). The curves are Breit-Wigner fits to the nonanalog transitions.

nonanalog and analog transitions,

$$^{16,18}\mathrm{O}(\pi^+,\pi^-)^{16,18}\mathrm{Ne(g.s.)}\ .$$

The new data are clearly similar to those for the pure nonanalog ^{16}O(π^+,π^-) case. At energies above 160 MeV, the nonanalog excitation functions decrease with energy, whereas the analog excitation function increases. The maximum cross section of the new excitation function occurs at about the same incident pion energy as for the ^{16}O data. There is no known significance, however, to the energy at which the maximum cross section occurs. A fit with a Breit-Wigner expression to the new excitation function gives a width of 88 MeV, which is slightly larger than the results presented in Ref. 3.

The 164-MeV, ^{18}O$(\pi^-,\pi^+)^{18}$C(g.s.) angular distribution is shown in Fig. 3, along with 164-MeV angular distributions for the reactions ^{16,18}O$(\pi^+,\pi^-)^{16,18}$Ne(g.s.). The new data exhibit a minimum near $\theta=30°$. The new angular distribution is much more similar to the nonanalog ^{16}O angular distribution than the analog ^{18}O angular distribution. Both the nonanalog angular distributions exhibit minima consistent with the nuclear size, whereas the analog angular distribution does not. The damped-Bessel-function curves through the new data and the ^{16}O data are, aside from a scale factor and kinematic differences, identical.

Finally, we discuss the mass dependence on nonanalog DCX. The expected ^{18}O$(\pi^-,\pi^+)^{18}$C(g.s.) cross section, calculated from the best fit formula given above (evaluated at mass 18), is $\sim$421 nb/sr. This is significantly less than the measured cross section, 621 ± 126 nb/sr. All data points on self-conjugate targets are within 17% of the best fit curve; the new point is larger by 48%. The new data point has an insignificant effect on the fit parameters since the six points on self-conjugate targets all have better statistics. Thus, an $A^{-4/3}$ mass dependence represents all the data well, but the ^{18}O$(\pi^-,\pi^+)^{18}$C(g.s.) cross section appears to be enhanced by 50% over cross

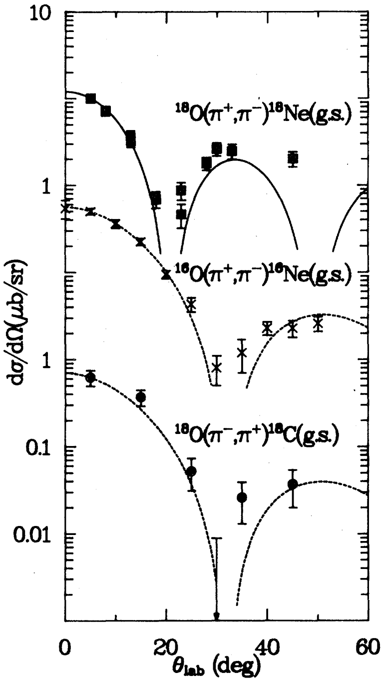

FIG. 3. Angular distribution for $^{18}O(\pi^-,\pi^+)^{18}C$(g.s.) at $T_\pi = 164$ MeV contrasted with previously measured angular distributions for $^{16}O(\pi^+,\pi^-)^{16}Ne$(g.s.) (Ref. 16) and $^{18}O(\pi^+,\pi^-)^{18}Ne$(g.s.) (Refs. 2 and 17). All curves are of the form $J_0^2(qR)e^{-qd}$, and have been normalized to the $\theta = 5°$ points. The dashed curves were calculated with $R = 3.3$ fm and $d = 1.2$ fm. The solid curve was calculated with $R = 4.9$ fm and $d = 0.0$ fm.

sections measured on self-conjugate targets.

With only one data point on a non-self-conjugate target, it is impossible to determine whether the enhancement is caused by nuclear structure effects or reaction mechanism effects. There may be isospin-dependent reaction mechanism effects that increase the cross sections of all $T = 1$ to $T = 3$ transitions relative to $T = 0$ to $T = 2$ transitions. Measurement of additional $T = 1$ to $T = 3$ transitions could settle this question. There is no evidence that nuclear structure effects significantly affect cross sections on self-conjugate targets. All data agree with the best fit within error bars. All but one (^{24}Mg) of the self-conjugate targets, however, have (in a simple picture) completely filled shell model orbits. If nonanalog DCX is analogous to two-particle transfer reactions, amplitudes are proportional to two-particle coefficients of fractional parentage. These are unity for targets with filled orbits, but greater than unity for targets with partially empty orbits. For example, if neutrons in ^{16}C, ^{18}C, and ^{18}O are all in the $1d_{5/2}$ orbital, the cross section for $^{18}O(\pi^-,\pi^+)^{18}C$(g.s.) would be 1.33 times that for $^{16}O(\pi^-,\pi^+)^{16}C$(g.s.). More realistic wave functions can give larger enhancements.

In conclusion, we have shown that the nonanalog DCX systematics observed in $T = 0$ to $T = 2$ transitions are a general feature of pion DCX, rather than an anomaly on a special class of target nuclei. The observed $A^{-4/3}$ mass dependence fits all observed data well, although the $^{18}O(\pi^-,\pi^+)^{18}C$(g.s.) appears enhanced over cross sections on self-conjugate targets. This suggests that (1) it would be interesting experimentally to measure nonanalog mass dependence on heavier nuclei (especially $T = 1$ targets), and (2) it would be interesting theoretically to do a microscopic calculation of the proposed reaction mechanism.

We thank Noby Tanaka and the MP-10 technical staff at LAMPF for installing the DCX modifications to the spectrometer and preparing the ice target. This work was supported in part by the U. S. Department of Energy, The Robert A. Welch Foundation, the National Science Foundation, and the Natural Sciences and Engineering Research Council of Canada.

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