Inclusive Pion Double Charge Exchange in ^{16}O and ^{40}Ca

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(Received 21 December 1984)

The first systematic study of inclusive pion double charge exchange in nuclei is reported. Doubly differential cross sections for the reactions $^{16}O(\pi^+,\pi^-)X$ and $^{40}Ca(\pi^+,\pi^-)X$ have been measured at incident pion energies of 120, 150, 180, 210, 240, and 270 MeV at three to five angles in the range from 25° to 130° with complete coverage of the outgoing pion energy spectrum. Similarly, the reactions $^{16}O(\pi^-,\pi^+)X$ and $^{40}C(\pi^-,\pi^+)X$ were studied at 180, 210, and 240 MeV at three angles.

PACS numbers: 25.80.Fm, 27.20.+n, 27.40.+z

Inclusive pion double charge exchange (DCX) contributes less than 1% to the total cross section for pion reactions in a nucleus such as ^{16}O at incident energies near the delta resonance.[1] This relatively rare reaction is interesting because at least two nucleons must be involved to conserve charge and the outgoing pion must not be absorbed. Therefore the cross section depends on the multiple scattering, and on the competition between scattering and absorption, of pions in nuclei.

The contribution of multiple interactions to the scattering of pions by nuclei has been difficult to elucidate. The free pion-nucleon cross section is very large at the delta resonance, so that pions propagating within a nucleus have mean free paths that are short compared with the dimensions of the nucleus. At the same time, pions are strongly absorbed, primarily by pairs of nucleons. Therefore, most of the pions that escape absorption to appear in the scattering channels have scattered from a single nucleon while the rest of the nucleus has participated only as a medium that modifies the free pion-nucleon interaction. For example, the outgoing pion energy spectrum in elastic scattering is dominated by a quasifree peak whose kinematic behavior strongly suggests the working of a simple one-collision mechanism.[2] Quasifree scattering also displays a small low-energy tail that appears to result from multiple scattering. In contrast, the lowest-order contribution to DCX is some form of two-nucleon interaction, so that multiple interactions may be observed in DCX unobscured by the much more prevalent single-nucleon processes.

Theories of inclusive double charge exchange are still primitive except, perhaps, for the double-scattering calculation of DCX in ^4He by Gibbs *et al.*[3] Confrontation with the sparse and uncertain data for ^4He that have been available[4] has not led to decisive conclusions. No microscopic calculation of DCX in heavier nuclei has appeared yet, although in principle either multiple-scattering or delta-hole methods could be applied.

Because theoretical analysis of pion multiple scattering is difficult, systematic observation of DXC in several nuclei is an important step toward identification of the essential features of the reaction. Apart from some early work with nuclear emulsions[5] the only previous measurement for nuclei heavier than helium is of the $^{16}O(\pi^+,\pi^-)X$ cross section at three angles with 240-MeV incident pions.[1] We report here a study of DCX in ^{16}O and ^{40}Ca designed to yield a systematic set of data covering a broad range of pion incident energies and outgoing angles. The reactions $A(\pi^+,\pi^-)X$ was observed at incident energies of 120, 150, 180, 210, 240, and 270 MeV, and the reaction $A(\pi^-,\pi^+)X$ was observed at 180, 210, and 240 MeV. Additional exploratory measurements were made with 180-MeV positive pions on ^{12}C and 180-MeV pions of both charges on natural lead. At each energy, doubly differential cross sections were measured at three to five angles over the entire range of outgoing energies from 10 MeV up to the kinematic limit for two-nucleon knockout at about 20 MeV below the energy of the incident pions. No attempt was made to resolve DCX to bound states, which makes a negligible contribution to the total DCX cross section in the energy range considered here.

These data[6] were acquired at the high-energy pion channel of the Clinton P. Anderson Meson Physics Facility. Pion fluxes of up to $10^9\ s^{-1}$ impinged on either a 1-g/cm^2 calcium target or a 1.5-g/cm^2 H_2O target. In the absence of pion-induced pion production, detection of a pion with charge opposite to that of the beam is a unique signature of DCX. The potential background from pion production is estimated[6] to be less than 20% at 270 MeV, and less than 5% at 240 MeV. It is surely much smaller at lower energies. No evidence of this reaction is seen, even at 270 MeV, where one might expect it to cause a change in the form of the outgoing-pion's energy spectrum.

Pions were detected by a 180° double-focusing spectrometer[7] instrumented with a wire chamber between its two dipoles, and a focal-plane array consisting of a pair of wire chambers, a plastic scintillation counter, and a threshold Čerenkov detector. The Čerenkov detector identified electrons that came primarily from conversion of π^0-decay photons. During measurements of $A(\pi^-,\pi^+)X$, a sizable contamination of protons and other light ions accompanined the positive pions. Measurement of the pulse height in the scintillator, and (at certain momenta) of the time of flight between the wire chamber at the center of the spectrometer and the scintillator, allowed a clear identification of this background.

In addition to a straightforward correction for pion decay in the relatively short 3.5-m flight path through the spectrometer, a correction of a few per cent for muons mistakenly identified as pions was made by use of a Monte Carlo simulation.[6] The relative beam intensity was measured by an ionization chamber upstream of the spectrometer and by a scattering monitor consisting of a pair of scintillator telescopes aimed at a CH_2 target downstream of the spectrometer. The monitors, together with the detection system as a whole, were calibrated for each energy and charge of incident beam by measurement of the angular distribution of pion-proton elastic scattering and comparison of the measurement with the prediction of an accepted phase-shift representation of the cross section.[8]

A sample of the data, showing doubly differential cross sections for the (π^+,π^-) reaction in ^{16}O and ^{40}Ca at five angles, each at an incident energy of 180 MeV, is given in Fig. 1. The (π^-,π^+) cross sections are similar in shape, but the peaks are shifted to higher outgoing-pion energies by about 10 MeV for oxygen and 25 MeV for calcium, as expected from the Coulomb effect. The solid curves represent the four-body phase-space distribution for the reaction $\pi^+ + (Z,N) \rightarrow \pi^- + p + p + (Z,N-2)$, normalized to the 50-MeV point in the 25° spectrum.

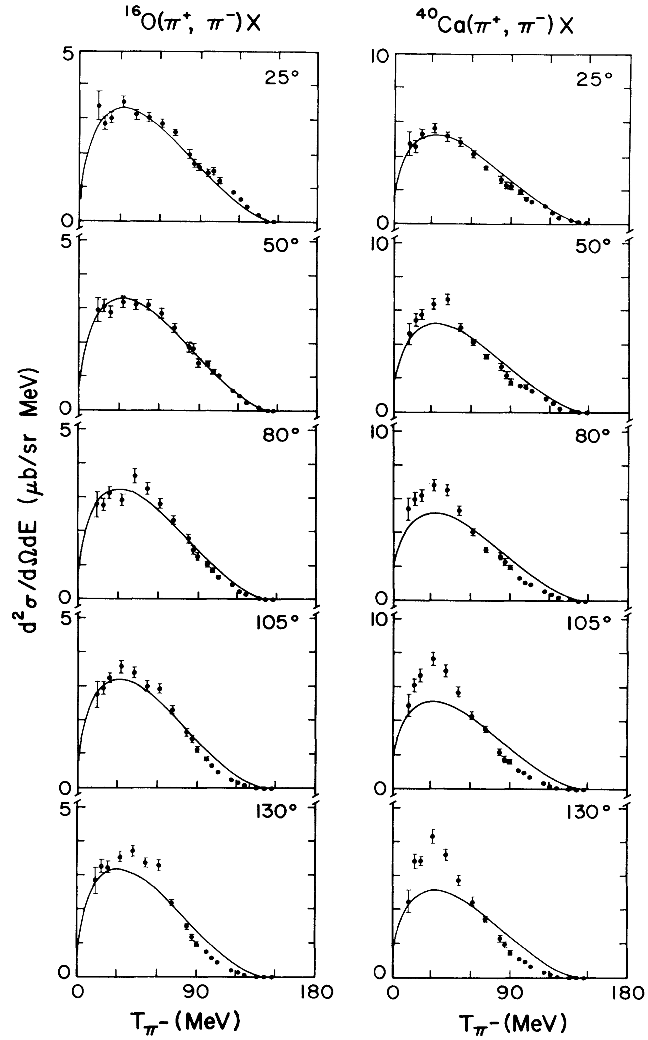

FIG. 1. Doubly differential cross sections for the reactions $^{16}O(\pi^+,\pi^-)X$ and $^{40}Ca(\pi^+,\pi^-)X$ at an incident energy of 180 MeV. The solid curves represent the distribution of events in four-body phase space, normalized to the point at 50 MeV in the spectrum at 25°.

Comparison with the four-body phase-space distribution is useful for displaying systematic features of the data. In general, the spectra qualitatively resemble this distribution; most of the DCX strength is concentrated in the low-energy end of the spectrum, in sharp contrast with both the quasifree scattering[2] and the inclusive single-charge-exchange reactions.[9] Although the position of the peak, located at about 1/4 the incident pion energy, does not noticeably change with angle, its amplitude grows with increasing scattering angle. This increase in the low-energy strength is accompanied by a decrease in the high-energy yield, which causes the angular distribution obtained by integrating these doubly differential cross sections over outgoing pion energy to be nearly isotropic. However, the oxygen angular distributions tend to be increasingly forward peaked at higher energies whereas the calcium angular distributions tend to be backward peaked (Fig. 2). In heavier nuclei the backward peaking of the angular distribution becomes more pronounced,[6] reaching a ratio of 1.3:1 between the 130° and 25° cross sections in the reaction $\mathrm{Pb}(\pi^+,\pi^-)X$ at 180 MeV. This behavior is consistent with a semiclassical picture in which DCX, and pion reactions in general, take place principally on the backward hemisphere of the nucleus where it is struck by the incoming pions. In the two-step DCX reaction pions scattered forward in the first interaction must propagate a large distance in the nucleus where they are subject to absorption. Thus DCX to small angles is inhibited, and more strongly so in a heavy nucleus than in a light one.

The angular distributions have been integrated in turn to yield total cross sections for DCX (Fig. 3). Whereas the energy spectrum of the outgoing pions when plotted as a function of the ratio of emitted to incident pion energies has a shape that is fairly independent of the beam energy, the magnitude of the integrated cross section is strongly energy dependent. From 120 to 270 MeV the cross sections for both oxygen and calcium rise nearly linearly, increasing by a factor of 5. This increase is in marked contrast to the primary pion-nucleus reaction channels, elastic scattering, quasifree scattering, single charge exchange, and absorption, whose cross sections either peak or level off near 165 MeV where the delta resonance is most strongly excited. The behavior of the DCX cross sections suggests that the importance of multiple-nucleon mechanisms increases rapidly as the incident pion energy is increased beyond the delta resonance.

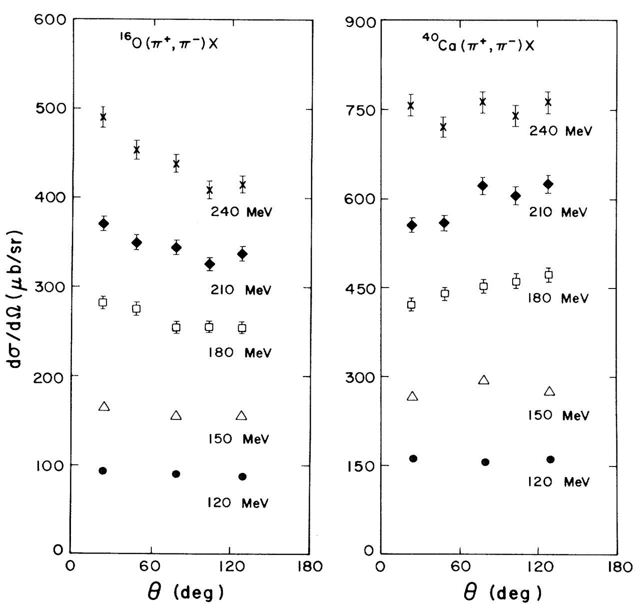

FIG. 2. Angular distributions of the reactions $^{16}\mathrm{O}(\pi^+,\pi^-)X$ and $^{40}\mathrm{Ca}(\pi^+,\pi^-)X$ at five incident energies.

The continuing rise of DCX cross sections above the energy of the resonance has been predicted by a semiclassical description of inclusive pion reactions using the Boltzmann equation.[10] To compare with our data for ^{16}O, the prediction for DCX in ^{12}C has been multiplied by a factor of $(\frac{16}{12})^{2/3}$ (Fig. 3). Although the theoretical curve rises with energy up to 200 MeV, it does not predict as steep a rise as is seen in the data, and it turns downward again at higher energy. The failure of this model at the higher energies is puzzling because semiclassical approximations presumably become more nearly valid there.

Despite the strong energy dependence of the DCX cross sections for both ^{16}O and ^{40}Ca, their ratio is independent of energy, within errors, over the region measured. The average ratio of $^{40}\mathrm{Ca}(\pi^+,\pi^-)X$ to $^{16}\mathrm{O}(\pi^+,\pi^-)X$ cross sections is 1.75, and that for the (π^-,π^+) reactions is 1.93. These ratios correspond to nuclear size dependences of $A^{0.61}$ and $A^{0.72}$, respectively, suggesting, at least for these $N=Z$ nuclei, that DCX scales approximately with their geometrical area.

In summary we have shown here a representative sample of an extensive collection of high-quality data

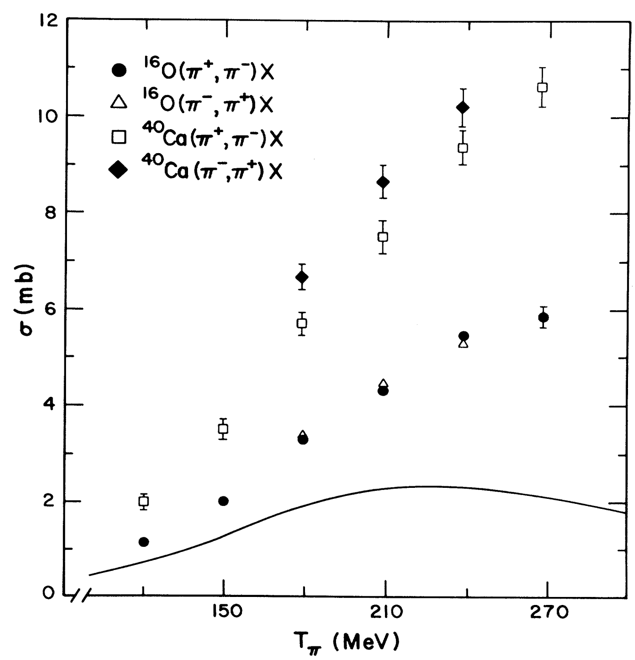

FIG. 3. Total double-charge-exchange reaction cross sections in ^{16}O and ^{40}Ca as a function of incident energy for both positive and negative pions. The solid curve is the prediction of Ref. 10 scaled by a factor of $(\frac{16}{12})^{2/3}$.

on inclusive DCX in ^{16}O and ^{40}Ca for incident pion energies between 120 and 270 MeV, and we have offered a qualitative discussion of some of its systematic features. Although the shapes of the outgoing-pion energy spectra observed for the two nuclei are similar, the cross sections exhibit different dependences on scattering angle and incident energy. The integrated cross sections for both nuclei increase almost linearly through the delta-resonance region. Although no dynamical calculations exist at present, systematic data of this nature, together with results anticipated for both lighter and heavier nuclei, are expected to have great value in revealing the mechanism of pion multiple scattering in nuclei.

This work was supported in part by the U. S. Department of Energy.

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