Dependence of the Cross Section for Inclusive Pion Double Charge Exchange on Nuclear Mass and Charge

P. A. M. Gram
Los Alamos National Laboratory, Los Alamos, New Mexico 87545

S. A. Wood,[a] E. R. Kinney,[b] S. Høibråten,[c] P. Mansky,[d] J. L. Matthews, and T. Soos
Massachusetts Institute of Technology, Cambridge, Massachusetts 02139

G. A. Rebka, Jr., and D. A. Roberts[e]
University of Wyoming, Laramie, Wyoming 82071
(Received 28 March 1988; revised manuscript received 20 March 1989)

Total reaction cross sections for inclusive pion double charge exchange have been obtained at incident pion energies of 180 and 240 MeV for ^{4}He, ^{6,7}Li, ^{9}Be, ^{12}C, ^{16}O, ^{40}Ca, ^{103}Rh, and ^{208}Pb. An explanation of the dependence of these cross sections upon the mass and charge of the target nucleus and the charge of the incident pion is suggested in terms of a phenomenological model in which successive single-charge-exchange processes compete with more probable processes such as quasifree scattering.

PACS numbers: 25.80.Ls

The strength of the elementary pion-nucleon interaction suggests, and analysis of pion-nucleus reactions confirms, that multiple scattering plays an important, if often indirect, role in all pion-nucleus reactions.[1,2] Inclusive pion double charge exchange (DCX) is of special interest because charge conservation alone demands that at least two nucleons explicitly participate in the reaction. Thus DCX provides a way to study directly multiple scattering in pion-nucleus reactions. At present, there is no adequate microscopic theoretical description of the multiple scattering of strongly interacting particles in nuclei. To promote and guide the construction of such a theory, it is useful to establish the systematics of DCX.[3,4]

An extensive set of measurements of the doubly differential cross sections for the inclusive DCX reactions (π^-,π^+) and (π^+,π^-) in nine nuclei ranging in mass from $A=4$ to 208 has been performed with incident pion energies between 120 and 270 MeV.[5-7] Angular distributions and total reaction cross sections have been derived from these data. In this paper we discuss the dependence of the total cross sections on the charge and mass of the target nucleus.

The doubly differential cross section $\sigma(T,\theta)$ was measured for each target and incident beam at several angles, θ, with complete coverage of the outgoing pion energy spectrum from $T=10$ MeV up to the kinematic limit for inclusive DCX. The measurements were performed using the high-energy pion channel at the Clinton P. Anderson Meson Physics Facility (LAMPF). Pions were detected by a 180° double-focusing spectrometer with a 3.5-m flight path from target to detectors. The spectrometer was instrumented with a wire chamber between its two 90° dipoles, and a focal-plane array consisting of a pair of wire chambers, a plastic scintillation counter, and two threshold Čerenkov counters. The experimental method is described in more detail in Ref. 5. Absolute cross sections were obtained by normalization with respect to π-p elastic scattering for each energy and charge of incident pion. The doubly differential cross sections $\sigma(T,\theta)$ were integrated over outgoing pion energy at each angle to yield singly differential cross sections $\sigma(\theta)$. These were fitted by sums of Legendre polynomials. Total reaction cross sections were obtained by integrating the fitted functions over angle.

In the simplest picture, double charge exchange proceeds as two successive quasifree single-charge-exchange (SCX) reactions. In the (π^+,π^-) process, the SCX reactions take place only on the neutrons, whereas in the (π^-,π^+) process, they take place only on the protons. Thus the probability of the first SCX reaction would be proportional to either N or Z, depending on the charge of the incoming pion, and the probability of the second interaction would be proportional to $N-1$ or $Z-1$. Therefore we might expect the cross section for DCX to be proportional to $Q(Q-1)$, where Q is the number of nucleons of the appropriate type.

Figure 1 presents the variation of the reaction cross sections with A for the (π^+,π^-) reaction at 180 and 240 MeV. The monotonic rise of the cross sections according to a power law in A is not unexpected. Only the cross sections for ^{7}Li and ^{9}Be, which have "extra" neutrons, deviate significantly, lying about a factor of 2 above the general trend. The surprising result is in Fig. 2. The cross sections for the (π^-,π^+) reaction rise approximately parallel to those for the (π^+,π^-) reaction up to about $A=40$, where they become constant and remain so up to $A=208$, despite the fact that Pb has over 4 times as many protons as Ca.

A possible explanation of the observed "saturation" of

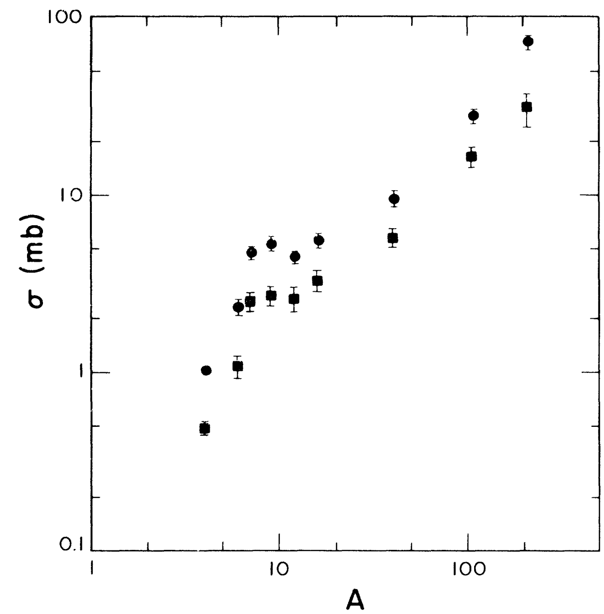

FIG. 1. Total inclusive cross sections for the $A(\pi^+,\pi^-)$ reaction at 180 MeV (solid squares) and 240 MeV (solid circles) as functions of A.

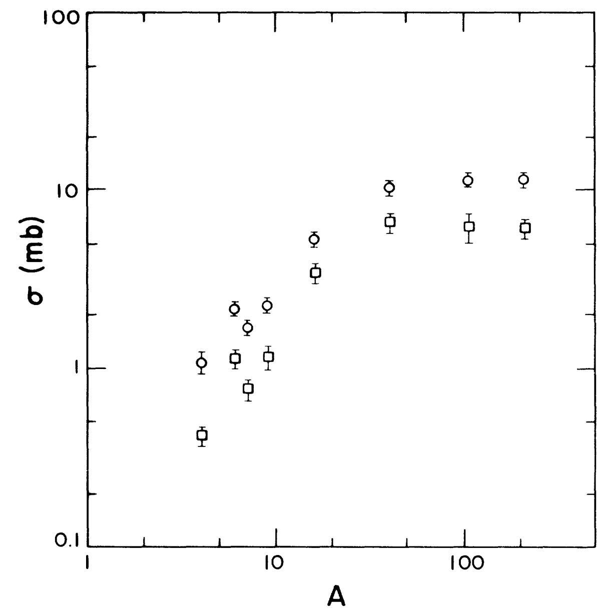

FIG. 2. Total inclusive cross sections for the $A(\pi^-,\pi^+)$ reaction at 180 MeV (open squares) and 240 MeV (open circles) as functions of A.

the (π^-,π^+) cross section is that the DCX process is inhibited by competing reactions that occur on the large number of excess neutrons found in heavy nuclei. At Δ-resonance energy, negative pions interact more strongly with neutrons than with protons, but it is the protons on which (π^-,π^+) reactions take place. Moreover, there is theoretical reason to believe that in heavy nuclei a fraction of the neutron distribution lies outside the proton distribution, further enhancing this effect. It is an interesting accident of nature that the resolution of this competition results in a cross section with zero slope for $A > 40$. Naturally, neutrons and protons exchange roles for positive incoming pions, but since there are no heavy proton-rich nuclei, the (π^+,π^-) cross section does not "saturate" at some value of A. A classical calculation[8] based upon this picture of successive SCX reactions competing with other processes predicts trends with increasing A similar to those observed, but the results are not in quantitative agreement with the data shown in Figs. 1 and 2.

We present a heuristic scaling rule to test these ideas. It is based on the simplification that reactions with one species of nucleon inhibit the first quasifree SCX reaction that must occur on the other species to result in double charge exchange. Thus a negative pion, for example, running the gauntlet of competing reactions, would have a probability of Z/N of completing the first SCX. The intermediate neutral pion thus formed, which according to isospin invariance interacts equally well with neutrons and protons, would have probability of $(Z-1)/(A-1)$ of completing the second SCX, leading to a positive pion in the final state. The overall probability that a negative pion will produce a DCX reaction would therefore be proportional to the product $Z(Z-1)/N(A-1)$. The projected area of a nucleus varies as $A^{2/3}$. Therefore the total reaction cross section for DCX should depend on the population of nucleons in a nucleus as

$$\sigma \propto A^{2/3}Q(Q-1)/(A-Q)(A-1)\,,$$

where $A-Q$ represents the number of "spectator" nucleons on which competing reactions occur. We have tested this formula by multiplying the total reaction cross sections by $(A-1)/A^{2/3}Q(Q-1)$ and plotting this quantity against $A-Q$. When fitted to the cross sections for nuclei with $A \geq 6$, the resulting power law is found to have the dependence $(A-Q)^{-1.04\pm0.03}$, at each incident energy. Figure 3 displays the results for both the (π^+,π^-) and (π^-,π^+) reactions at 180 and 240 MeV. In these graphs, cross sections for both charges of incident pion occur at the same values of $A-Q$ for $N=Z$ nuclei but at different values of $A-Q$ for $N>Z$ nuclei. With the notable exception of ^{4}He, all of the cross sections at a particular energy, including those for ^{7}Li and ^{9}Be, are adequately described by this parametrization. This simple rule succeeds in reconciling the behavior of the quite different cross sections for the (π^+,π^-) and (π^-,π^+) reactions. The deviation of the ^{4}He data remains unexplained, resulting perhaps from the failure of simple statistical concepts in this small nucleus.

We are far from quantitative understanding of the reaction mechanisms at work in inclusive DCX, but the success of this simple picture suggests that sequential

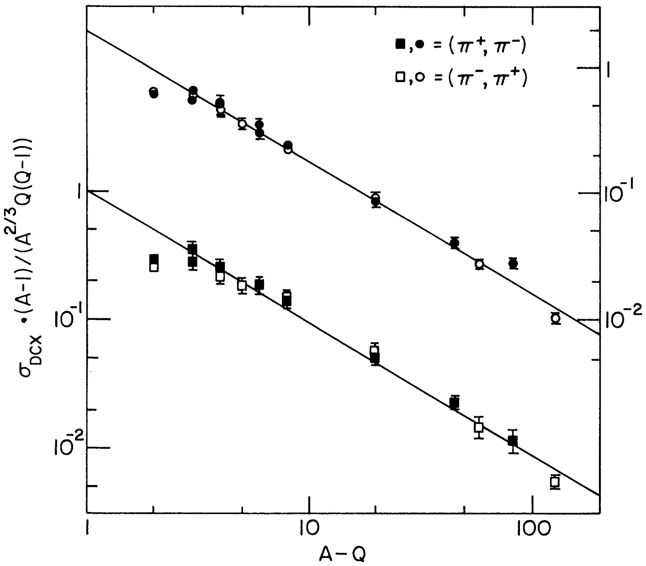

FIG. 3. Total inclusive cross sections at 240 MeV (upper points and line, right-hand scale) and 180 MeV (lower points and line, left-hand scale), multiplied by $(A-1)/A^{2/3}Q(Q-1)$, plotted against $A-Q$, where $Q=N$ for (π^+,π^-) and $Q=Z$ for (π^-,π^+). The ratios for nuclei with $A \gtrsim 6$ are fitted by a power law whose dependence is found to be $(A-Q)^{-1.04\pm0.03}$, close to the predicted value of -1, with $\chi^2=1.5$ per degree of freedom at each incident energy.

single charge exchange operating in competition with more probable processes such as quasifree scattering is a useful idea with which to begin.

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

[(a)]Present address: University of Illinois, Champaign, IL 61820.
[(b)]Present address: Argonne National Laboratory, Argonne, IL 60439.
[(c)]Present address: University of Colorado, Boulder, CO 80309.
[(d)]Present address: Princeton University, Princeton, NJ 08544.
[(e)]Present address: University of Michigan, Ann Arbor, MI 48109.

[1]M. Baumgartner *et al.*, Nucl. Phys. **A399**, 451 (1983).
[2]M. Thies, Nucl. Phys. **A382**, 434 (1982).
[3]J. L. Matthews, in *Proceedings of the LAMPF Workshop on Pion Double Charge Exchange* (Los Alamos National Laboratory Report No. LA-10550-C, 1985).
[4]P. A. M. Gram, in *Pion-Nucleus Physics: Future Directions and New Facilities at LAMPF, Los Alamos, New Mexico, 1987,* edited by R. J. Peterson and D. D. Strottman, AIP Conference Proceedings No. 163 (American Institute of Physics, New York, 1988), p. 79.
[5]J. B. Walter, Los Alamos Scientific Laboratory Report No. LA-8377-T, 1979 (unpublished); D. M. Manley, Los Alamos National Laboratory Report No. LA-9101-T, 1981 (unpublished); S. A. Wood, Los Alamos National Laboratory Report No. LA-9932-T, 1984 (unpublished).
[6]S. A. Wood *et al.*, Phys. Rev. Lett. **54**, 635 (1985).
[7]E. R. Kinney *et al.*, Phys. Rev. Lett. **57**, 3152 (1986).
[8]F. Becker and Yu. A. Batusov, Riv. Nuovo Cimento **1**, 309 (1971).