Pion Double Charge Exchange on ^{4}He and Meson Exchange Currents

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We have measured the differential cross section $d^2\sigma/d\Omega\, dT$ and estimated the total cross section σ_T for the double charge exchange reaction $^4\text{He}(\pi^+,\pi^-)4p$ at 140, 200, and 295 MeV. The values for σ_T are at least an order of magnitude larger than predictions based on sequential single charge exchange π-N scatterings. It is possible, therefore, that $^4\text{He}(\pi^+,\pi^-)$ is dominated by other processes, such as the formation of a Δ in the intermediate state or scattering from meson exchange currents.

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Since nuclei are bound by the exchange of mesons it is reasonable to assume that, even in their ground states, nuclei should have some measurable properties due to their mesonic degrees of freedom. The search for "mesons in nuclei" has concentrated on corrections to nuclear magnetic moments, photonuclear reactions and sum rules, and low-energy electron scattering.[1] The mesonic effects, however, are usually small and always model dependent. Calculations that are sensitive to meson exchange currents are frequently sensitive to poorly known details of the nuclear wave functions as well.

One promising class of reactions for studying meson exchange effects is pion double charge exchange. Conservation of charge automatically rules out the "first-order" processes that usually mask the weaker exchange effects. Recent work on double charge exchange has centered around transitions to discrete nuclear states. However, these cross sections are very small, and the nuclear-structure complications inherent in these transitions have made it unrealistic to use double charge exchange as a probe of exchange currents. There are some double charge exchange transitions between light nuclei and *continuum* states, however, which might be simple enough for a detailed study of the reaction mechanism. Double charge exchange on ^{4}He, as proposed by Germond and Wilkin,[2] has been the most widely studied. But even here the data are sparse and apparently inconsistent.

We have recently completed an experiment on double charge exchange on ^{3}He and ^{4}He using the EPICS pion spectrometer at the Clinton P. Anderson Meson Facility. We report here our results for the total cross sections for the reaction $^4\text{He}(\pi^+,\pi^-)4p$, which can be compared directly with the work of Germond and Wilkin as well as with several other theories that assume other reaction mechanisms.

The EPICS spectrometer has already been used in several double charge exchange experiments.[3] We mention only a few features that are peculiar to this experiment. Since we are interested in continuum states, it was necessary to use as much of the spectrometer acceptance as possible. The acceptance depends mainly on the deviation $\delta=(p-p_0)/p_0$ from the central momentum p_0. It was calibrated over the range $\delta=-0.08$ to $+0.11$

by measuring the $^{12}C(\pi, \pi)$ elastic cross section at fixed energy and angle, and varying the spectrometer field. The data have all been corrected by using this acceptance profile. The maximum correction at the edge of the acceptance is a factor of 4.5 relative to the center.

A substantial number of the low-momentum pions decay in the spectrometer. Although the cross sections are corrected for this decay, the muons are a potential source of contamination because the data consist of smooth continuum distributions. We used two criteria for discriminating between pions and muons: The first is based on trajectory reconstruction. The azimuthal and polar pion-scattering angles were measured in two independent ways: once by a set of wire chambers located between the spectrometer quadrupole and dipole, and again by the wire chambers after the dipole. These two measurements were required to agree to within 24 mrad. This effectively eliminates all muons resulting from pion decay in the dipole. At momenta below 195 MeV/c muons were also separated unambiguously from pions by means of time of flight through the spectrometer. At higher momenta there is a small contamination of the data by muons resulting from pion decay before the first wire chambers. At 195 MeV/c the fraction of events due to muons that had passed all the wire-chamber tests was 10%. This is the maximum level of muon contamination, since at higher momenta the increasing pion survival fraction more than compensates for the lower rejection efficiency due to the shrinking decay cone.

The relative pion flux was monitored with an ion chamber in the beam. The differential cross sections were normalized at each energy by comparison with pion-proton scattering from a CH_2 target of known thickness. The π-p differential cross sections are presumed known from phase shift compilations.

The cryostat used in this experiment has been described elsewhere.[4] It contained two cells ($15.2\times12.7\times2.5$ cm^3) for ^{3}He and ^{4}He which were kept at a temperature of 1.5 °K. From the target thicknesses determined from x-ray pictures, the effective target densities over the beam spot size (6.2×11.0 cm^2) were determined to be 311 and 574 mg/cm^2 (±5%), respectively, for ^{3}He and ^{4}He. The thin (25 mg/cm^2) aluminum-cell windows contributed a small amount to the double-charge-exchange cross sections. These contributions were subtracted with the help of short runs made with a thick aluminum target. This subtraction ranged from 10% at 295 MeV incident pion energy to virtually nothing at lower energies.

A typical spectrum is shown in Fig. 1. Here we have plotted the differential cross section $d^2\sigma/d\Omega\, dT$ vs T at a fixed scattering angle. The energy variable T is the "missing mass," i.e., the difference between the total invariant mass of the recoiling four-proton system and the rest mass of four protons. This is equivalent to the total kinetic energy of the protons in their own center-of-mass coordinate system. The data in Fig. 1 include seven overlapping spectrometer settings, but even so the last 40 MeV of missing mass was not measured because of the difficulty of detecting low-energy pions in the spectrometer. To obtain $d\sigma/d\Omega$ we integrated the spectra over T using an estimate for the cross section in the unmeasured region. The estimate was made by fitting the high missing-mass portion of the spectrum with the three-body (two nucleons and a pion) phase-space distribution, which is the smooth curve in Fig. 1. All of the ^{4}He($\pi^+\pi^-$) data are qualitatively similar to those plotted in the figure. In every case the phase-space curve is an excellent fit to the higher missing-mass data, while the small-missing-mass cross sections are suppressed relative to phase space. This indicates that even at 295 MeV, double charge exchange is primarily a two-nucleon reaction with very little energy transferred to the spectator nucleons. Both the four- and five-body phase space distributions are strongly peaked in the high missing-mass range and show no similarity to the data.

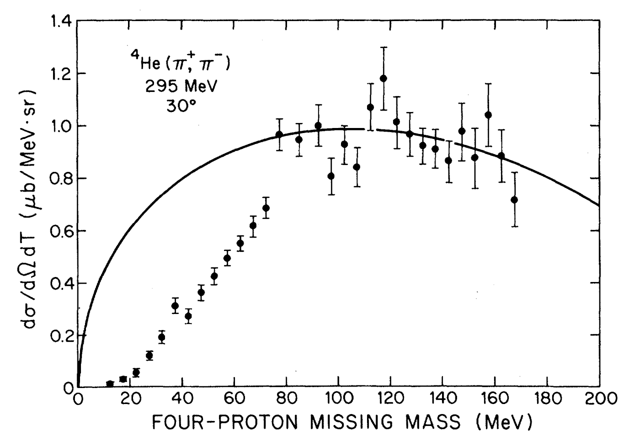

FIG. 1. The $d^2\sigma/d\Omega\, dT$ data plotted vs T for an incident energy of 295 MeV and a laboratory scattering angle of 30°. The smooth curve is a three-body phase-space distribution fit to the data points with T greater than 80 MeV.

TABLE I. Differential cross sections.

Incident energy (MeV)	Laboratory scattering angle (degrees)	$d\sigma/d\Omega$ (μb/sr)	Statistical error (μb/sr)	Extrapolation error (μb/sr)
140	20	10.2	± 0.6	1.0
200	30	45.3	1.9	5.1
200	80	32.3	1.5	4.7
200	120	23.0	1.5	3.7
295	30	155.9	3.2	18.5
295	80	105.7	4.4	7.6
295	120	70.1	3.2	8.4

The suppression in the low missing-mass region is presumably due to Pauli blocking in the tightly bound ^{4}He nucleus.

In an experiment such as this in which only one pion is detected it is possible in principle to confuse double-charge-exchange events with those involving pion production, such as ^{4}He$(\pi^+, \pi^-)\pi^0$, $4p$, and ^{4}He$(\pi^+, \pi^-)\pi^+$, $3p$, n. This is only possible kinematically when the missing mass calculated from the single observed pion exceeds the rest mass of the unobserved pion. This only affects our 295-MeV data, and then only over a relatively small region of the missing-mass plot. There is no sign of an increase in cross section over this range, which suggests that pion production is not an important source of background. We have also measured the 295-MeV cross section for ^{3}He(π^+, π^-), which can proceed only through pion production. We find that $d^2\sigma/d\Omega\, dT$ is less than 10% of the corresponding cross section for ^{3}He(π^-, π^+) for all observed T. If the ratio of pion production to double charge exchange is the same for ^{3}He and ^{4}He, then the contamination in the integrated 295-MeV ^{4}He cross sections must be less than 7%.

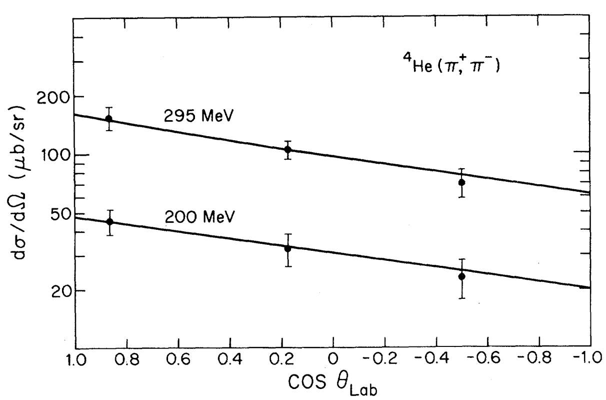

FIG. 2. $d\sigma/d\Omega$ vs $\cos\theta_{\rm lab}$ at 200 and 295 MeV. The curves are the predictions of a three-body phase-space distribution normalized to the data at each energy.

The integrated cross sections are listed in Table I. We list separately the statistical error and an estimate of the uncertainty resulting from the extrapolation of $d^2\sigma/d\Omega\, dT$ into the unmeasured region. In order to obtain the total cross section we fitted the experimentally determined values of $d\sigma/d\Omega$ with the three-body phase-space distribution and integrated the phase space to obtain σ_T. The fits are shown in Fig. 2. The phase space reproduces the trends of the data points, which show no angular structure except for slight forward peaking that increases with increasing energy. The value for σ_T at 140 MeV is derived from a single data point at 20°. Our results for σ_T are listed in Table II and plotted in Fig. 3 together with some data from other experiments.

There are two important mechanisms to consider in calculating double charge exchange at low energies, namely two successive single-charge-exchange interactions, and scattering from meson exchange currents. The first reaction mechanism has been discussed by Becker and Schmit[5] and by Gibbs *et al.*[6] Although these two calculations appear superficially similar, they predict total cross sections which differ by as much as three orders of magnitude. The more recent calculation by Gibbs *et al.*[6] contains some technical improvements over the original

TABLE II. Total cross sections.

Incident energy (MeV)	σ_T (μb)	Statistical error (μb)	Extrapolation error (μb)
140	89.9	5.5	9.2
200	398.0	11.2	51.4
295	1287.4	22.1	136.2

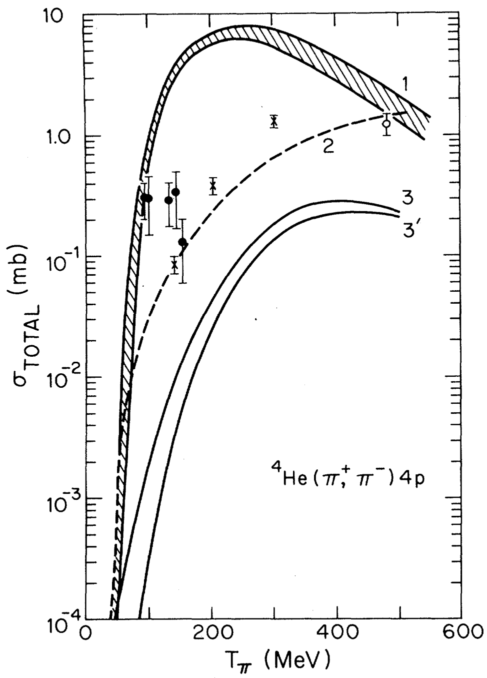

FIG. 3. Total cross section vs incident energy. The solid data points are from Falomkin *et al.* (Ref. 8), the open point from Carayannopoulos *et al.* (Ref. 9), and the data with crosses are from the present experiment. The curve labeled 1 is the prediction of Becker and Schmit (Ref. 5), 2 is from Germond and Wilkin (Ref. 2), and 3′ and 3 are predictions of Gibbs *et al.* (Ref. 6), with and without Pauli blocking corrections.

work of Becker and Schmit.[5] These include completely antisymmetrized wave functions, exact treatment of a five-body phase space, and a more complete parametrization of the π-N t matrix. The combined effect of these factors is to reduce the cross section by $(2300)^{-1}$ in general agreement with the 140-MeV data of Kaufman, Perez-Mendez, and Sperinde.[7] Unfortunately, it now appears that these data are wrong. We have reproduced the kinematic conditions of the experiment in Ref. 7 in order to check their surprisingly small cross sections. Our cross sections are larger by exactly 10^2 and are consistent with the earlier data of Falomkin *et al.*[8] and Carayannopoulos *et al.*[9] Taken together these data span a range of 400 MeV and are at least an order of magnitude larger than the predictions of Gibbs *et al.*

A simple calculation based on pion exchange scattering has been done by Germond and Wilkin.[2] They neglect the two "spectator" nucleons in the target and hence also the effects of the Pauli principle, rescattering, and five-particle phase space. They predict total cross sections that are intermediate between those of Gibbs *et al.* and Becker and Schmit and achieve the best overall agreement with available data. The agreement at low energies must be largely fortuitous, however, because the proper treatment of Pauli principle and phase-space effects would have suppressed the prediction at low energy.

If the calculation of Gibbs *et al.* is a valid indication of the strength of the sequential single-charge-exchange mechanism, then we must conclude that double charge exchange on ^4He is dominated by a more exotic process, presumably scattering from meson exchange currents. On the other hand there must be a large margin of uncertainty in these calculations judging from the difference between the results of Becker and Schmit and Gibbs *et al.* It is possible that other mechanisms such as virtual pion[10] or delta[11] production might also make an important contribution to the cross section at higher energies. Clearly we cannot weigh these contributions on the basis of existing calculations. More theoretical work is required in which all of the reaction mechanisms are included and treated with the same approximations. If these calculations confirm that sequential single charge exchange contributes a relatively small fraction to the observed cross sections, then double charge exchange could become an important probe of mesonic effects within the nucleus.

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