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104

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ABSTRACT

Nuclear pion single charge exchange has been studied using a method of π^0 detection based on the spectroscopy of the back-angle decay γ -ray. Charge exchange scattering from nuclei ranging from Be to Pb was studied for incident pion energies of 50, 100, 150, and 200 MeV. The angular distributions and π^0 energy spectra beyond 60° are dominated by effects characteristic of quasi-free scattering. Total charge exchange cross sections are larger than values suggested by optical model calculations.

I. INTRODUCTION

Almost all recent theoretical speculation on pion single charge exchange has focussed on reactions involving single charge exchange to specific final states, in most cases transitions to isobaric analogue states. While these

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exclusive reactions have also received most of the experimental attention, as evidenced by the program in this workshop, such reactions represent a very small fraction of the total charge exchange cross section. Almost no information exists on the broad outlines of single charge exchange reactions such as values of total cross sections and their mass dependence, the basic character of charge exchange reactions, e.g. the importance of quasi-free charge exchange scattering and multi-step charge exchange processes; and the importance of single charge exchange in describing the propagation of pions in nuclear matter. Such information should provide valuable insights into the reaction mechanism for single charge exchange. It will indicate the extent to which single charge exchange contributes to the total reaction cross section for pion-nucleus interactions. Furthermore, reliable estimates of quasi-free charge exchange cross sections will provide useful constraints when optical model potentials are used to describe pion-nucleus scattering. Because pion single charge exchange scattering is generated by the isovector component of the pion-nucleus interaction, it offers a very effective probe for studying the isospin structure of the optical model potential.

II. EXPERIMENTAL METHOD

We recently completed a series of measurements at LAMPF in which we measured directly the π^0 energy spectrum and angular distribution by means of the spectroscopy of the decay γ -rays emitted at back angles, the so-called BAG technique. Although this technique is not capable of the high resolution necessary to resolve individual states, it will permit the observation of scattering involving excitations averaged over intervals of approximately 5 MeV. The method we developed takes advantage of the fact that the decay photons emitted at back angles are strongly Doppler shifted to low energies so that they can be measured with conventional sodium iodide spectrometers. Figure 1 shows the photon energy contours as a function of the opening angle between the two decay photons. The idea of the measurement is to restrict the decay opening angle to values near 180° where the back scattered photon is strongly Doppler shifted, and to use sodium iodide spectrometers to measure the energy spectrum of these photons and from them deduce the π^0 energy spectrum. For π^0 energies between 50 and 200 MeV, the corresponding decay photon energies at back angles will range from 30 to 15 MeV.

The experimental configuration is shown in Fig. 2. It consists of two cylindrical photon detectors viewing a target which lies on their common axis of symmetry. The high energy photon is observed in a crude Pb-glass spectrometer while the low energy photon is observed with a large volume sodium iodide spectrometer. The photon opening angle was restricted to a range of 170° to 180° . Under these conditions for all but the lowest energy π^0 's the high energy photon is emitted within a few degrees of the angle of emission of the original π^0 . In essence, the π^0 energy spectrum is obtained from the spectrum of photon energies observed in the sodium iodide, and the π^0 angular distribution is determined from the direction of the high energy photon observed in the lead glass shower counter.

The measurements were carried out on the low energy pion channel of the Clinton P. Anderson meson physics facility using pion fluxes of approximately 2×10^7 pions per second with incident energies ranging from 50 to 200 MeV. Two NaI lead glass detector pairs were used in the measurements. The NaI(tl) crystals were 25 cm in diameter and 30 cm thick, and were surrounded by a plastic anticoincidence shield. The energy resolution of the spectrometers was about 3.8% at 23 MeV (the energy corresponding to a 100 MeV π^0) when operated in the "anticoincidence mode". Figure 3 shows a contour plot of events observed with a carbon target. The energy spectrum of the lead glass detector is indicated vertically and the energy spectrum of the sodium iodide spectrometer plotted horizontally. As indicated in the figure, there is a clean clear contour for π^0 events at just the position expected with the expected limits on photon energies.

Figure 4 shows a π^0 spectrum observed for π^- charge exchange on the proton. The energy resolution and efficiency calibration of the experiment were established by a $\text{CH}_2\text{-C}$ difference measurement of the reaction $\pi^- p \rightarrow \pi^0 n$ using cross sections calculated from known π -nucleon phase shifts. Figure 4 shows the decay photon spectrum observed for π^0 's emitted at 120° following charge exchange involving incident pions at 100 MeV. The resolution observed when the kinematic effects are removed corresponds to 5.2 MeV.

III. DATA

In the first measurements already published,¹ data were taken with a 100 MeV π^+ incident beam for π^0 angles of emission of 40° and 120° . Spectra were

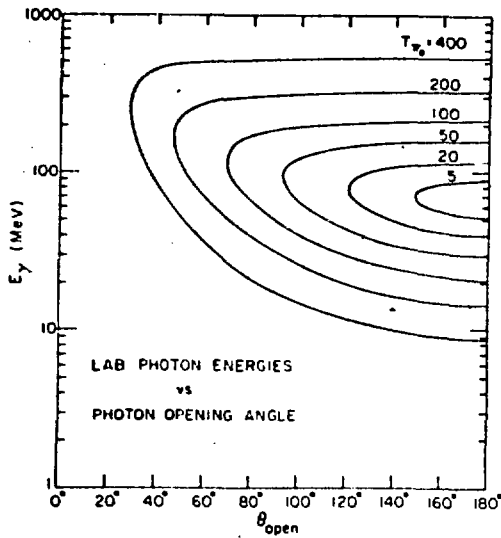


Fig. 1.
Plot of energies of π^0 decay photons as a function of photon opening angle for various π^0 kinetic energies.

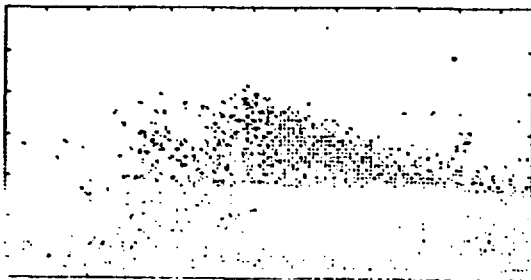


Fig. 3.
Two-dimension contour plot of Pb-glass (vertical) versus NaI (horizontal) pulse heights for π^0 spectrum resulting from 100 π^+ 's interacting with carbon.

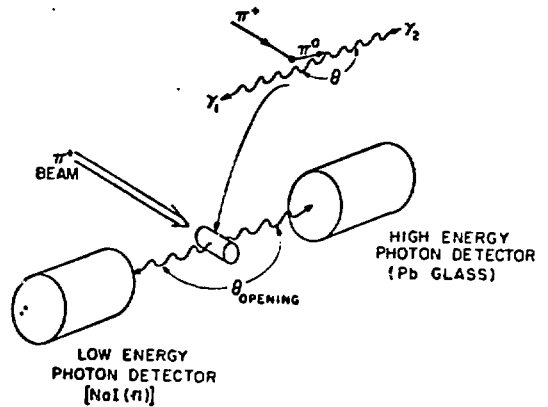


Fig. 2.
Experimental configuration showing a single π^0 detector pair. The inset shows a typical event and the corresponding photon opening angle, θ .

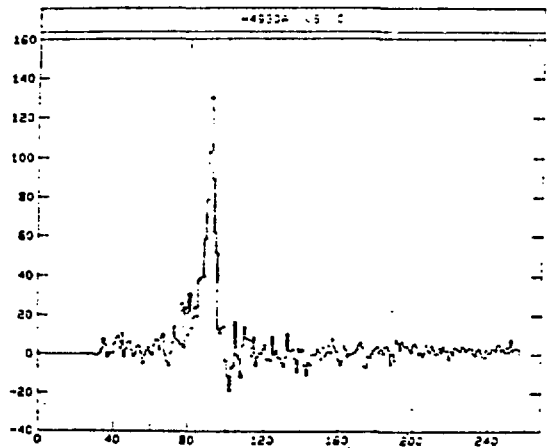


Fig. 4.
Decay photon spectrum observed for π^0 's emitted at 120° in the reaction $\pi^-p \rightarrow \pi^0n$ at 100 MeV.

taken with π^+ on Be, C, O, ^{58}Ni , and ^{208}Pb and with π^- on CH_2 and C. For all targets, the spectra had the same gross shape, (see for example the cross sections measured for ^{16}O shown in Fig. 5) roughly described as a peak about 60 MeV wide centered at about 60 MeV. However, the average π^0 energy was slightly greater at 40° and the shape somewhat flatter. Figure 6 shows energy-integrated π^0 cross sections per target neutron at the two angles measured for each of the targets studied. The cross section varies as $A^{-0.4}$ at both angles. The π^0 yield is backward peaked with the ratio $(d\sigma/d\Omega)_{40^\circ}/(d\sigma/d\Omega)_{120^\circ}$ virtually constant at 0.3, near the value of the free-nucleon reaction $\pi^- p \rightarrow n\pi^0$. The observation that the 120° differential cross sections peak near the momentum transfer appropriate to a free-nucleon reaction and that the angular distribution is backward peaked in a manner similar to that observed for the pion-nucleon process were interpreted as evidence that single charge exchange at this energy is dominated by a quasi-free reaction mechanism.¹

In order to explore the reaction mechanism in more detail and determine the importance of quasi-free scattering with more certainty, we have made an extensive survey of CEX studying the targets Be, ^{16}O , ^{58}Ni , and ^{208}Pb for

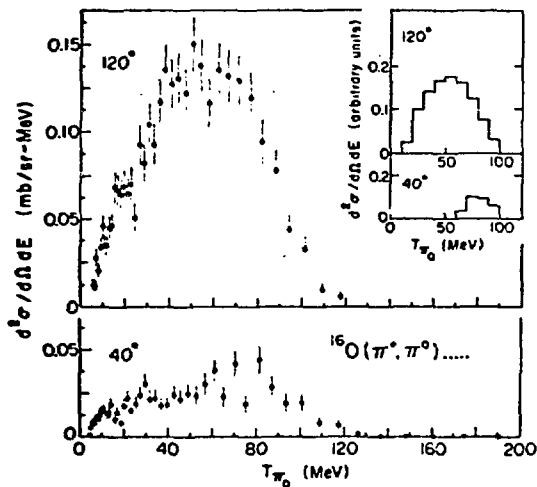


Fig. 5.
Differential cross section for single charge exchanges by ^{16}O at 40° and 120° . The inset shows the cross-section shapes calculated for charge-exchange scattering by a Fermi gas.

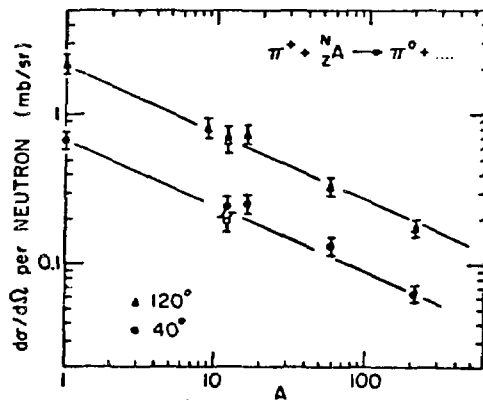


Fig. 6.
Differential cross section for single charge exchange as a function of atomic mass. The points for $A = 1$ are based on the assumed equality of $\pi^- + p \rightarrow \pi^0 + n$ and $\pi^+ + n \rightarrow \pi^0 + p$. The open points for $A = 12$ were taken with negative pions.

various combinations of positive and negative incident pions at energies in the range 50-200 MeV. Although the analysis is far from complete, preliminary results are presented here. A primary objective was to establish the role of quasi-free scattering by comparing the π^0 angular distributions with those which characterize the pion-nucleon reaction. Figure 7 shows the differential cross section for the $\pi^- p \rightarrow \pi^0 n$ reaction in the nucleon rest system calculated from known π -nucleon phase shifts² for incident pion energies of 50, 100 and 150 MeV. A strong interference between s and p-wave partial waves below the $\Delta(3,3)$ resonance produces the strong backward peaking which characterizes the curves for 50 and 100 MeV pions. As the $\Delta(3,3)$ resonance energy is approached, the cross section becomes forward peaked.

Of course in nuclear matter these distributions will be distorted by effects due to absorption and Pauli-blocking, particularly in the forward direction.³ Figure 8 shows the results of a simple calculation of charge exchange scattering by a proton-neutron Fermi gas. The energy and angular dependence of the differential cross sections were taken from π -nucleon phase shifts and the effects of Pauli-blocking were included in the computation. For scattering beyond 90° , Fermi broadening produces an energy spectrum that spans essentially the complete range of energy transfers, and Pauli-blocking reduces the scattering at forward angles. Figure 9 shows the energy-integrated

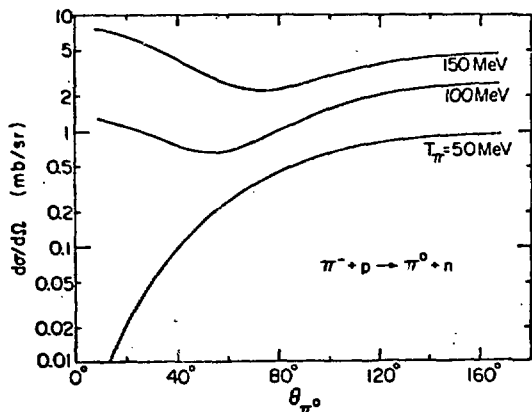


Fig. 7.

Differential cross sections for free nucleon pion charge exchange calculated from pion nucleon phase shifts.

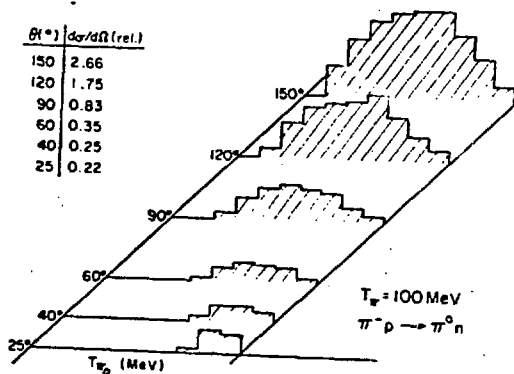
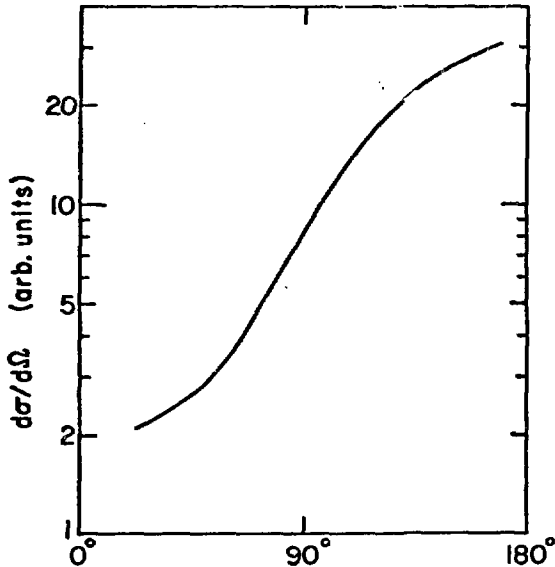


Fig. 8.

Energy distributions of π^0 at selected emission angles resulting from charge exchange by a zero temperature Fermi gas.

cross sections which result from the Fermi-gas calculation. The angular distribution is now very strongly backward peaked and the $d\sigma(120^\circ)/d\sigma(40^\circ) = 3.2$ ratio for the free nucleon process is to be compared with 7.0 for scattering by the Fermi gas. Of course such a simple calculation using the infinite nuclear matter density probably overestimates the nuclear binding effects.

The new data for ^{16}O taken for 100 MeV incident π^+ is shown in Fig. 10. These new results confirm earlier conclusions⁴ that the angular distribution for charge exchange is strongly backward peaked. Although the angular distribution is quite close to that of free nucleon charge exchange, we do not believe that we are seeing only quasi-free scattering at the forward angles. The energy spectra for π^0 emitted at forward angles is much too broad to be consistent with such a one step process. The inset of Fig. 5 shows the expected shape for Fermi-gas scattering and it is much narrower than the distribution measured at 40° . The data for ^{16}O shows in Fig. 11 supports such an interpretation. At 50 MeV, the cross section for the free nucleon process falls very rapidly at forward angles, while experimentally there is a substantial cross section in this region.



FERMI GAS CHARGE EXCHANGE

Fig. 9.

π^0 angular distribution predicted for charge exchange of 100 MeV π^+ by a zero temperature Fermi gas.

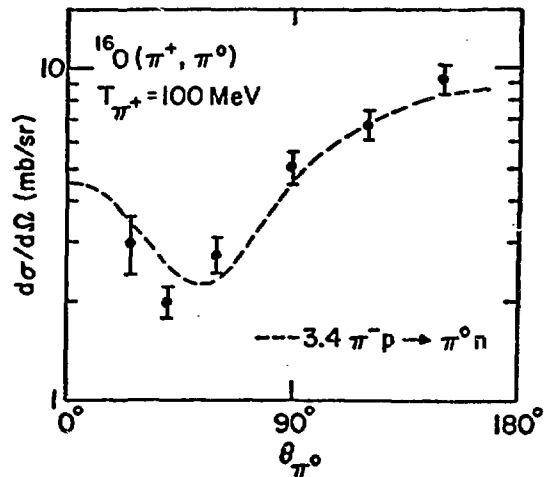


Fig. 10.

Angular distribution of single charge exchange on ^{16}O at 100 MeV.

The results for ^{58}Ni are shown in Fig. 12. Again the angular distribution is strongly backward peaked and has essentially the same shape as the ^{16}O data. There appears to be little charge dependence in the charge exchange cross section. Within statistics, the points for π^- and π^+ are identical. The π^0 energy spectra for ^{58}Ni have essentially the same features as those of ^{16}O . Thus, it appears from the angular distributions and the π^0 energy spectra that at these energies π -nucleus charge exchange favors large momentum transfer. The total inclusive charge exchange appears to be dominated by the quasi-free scattering which occurs at back angles.

The total charge exchange cross sections inferred from our data can be used to estimate the contribution of charge exchange to pion-nucleus reaction cross sections. Furthermore, they can provide valuable tests of current optical model potentials used to describe pion-nucleus scattering. For example, frequently one constructs a first order optical potential by assuming only s- and p-wave interactions and using free nucleon scattering amplitudes of the form

$$f_{\pi n} \approx (b_0 + b_1 \underline{\tau} \cdot \underline{t}) + (c_0 + c_1 \underline{\tau} \cdot \underline{t}) \underline{k} \cdot \underline{k}'$$

where the isospin and momentum operators have their usual meaning. The leading terms of the resulting potential are a scattering potential, $V_s(r)$, plus a true absorption term

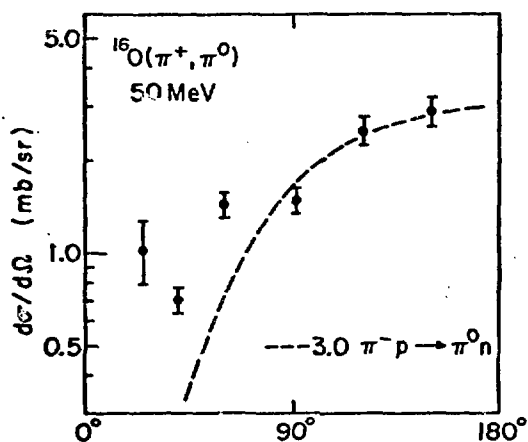


Fig. 11.
Single charge exchange cross section for ^{16}O at 50 MeV.

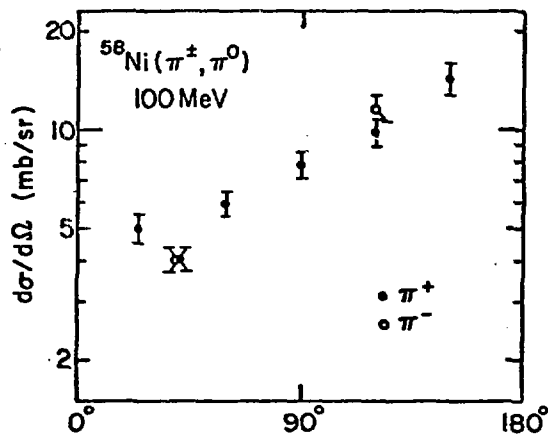


Fig. 12.
Single charge exchange cross section for ^{58}Ni at 100 MeV.

$$V_{\text{opt.}}(\mathbf{r}) \approx V_s(\mathbf{r}) + V_{\text{abs.}}(\mathbf{r}) + \text{higher terms.}$$

The true-absorption - " $\rho^2(\mathbf{r})$ " term can be determined phenomenologically or by using second order scattering theory. The scattering term usually has the form of the Kissinger potential with coefficients involving isoscalar and isovector terms:

$$V_s(\mathbf{r}) = B_0 k^2 \rho(\mathbf{r}) + \vec{\tau} \cdot B_1 \rho(\mathbf{r}) \vec{\tau}$$

$$B_0 \propto [a + b(\underline{\tau} \cdot \underline{\tau})] \quad B_1 \propto [c + d(\underline{\tau} \cdot \underline{\tau})].$$

The important point is that these coefficients are complex and the imaginary parts can be interpreted as describing the quasi-free π -nucleon scattering which removes flux from the elastic scattering channel. To the extent that an optical model is valid, one can estimate the quasi-free scattering from this term. Since CEX arises solely from the isovector term, its observation and comparison with the total inelastic pion scattering should put some constraint on the isospin structure of the optical model. Unfortunately particularly at lower energy, frequently the isovector part of the potential is omitted, i.e. charge exchange is neglected completely.

Table I shows the data analyzed to date. The total cross sections were obtained by integrating the corresponding angular distributions. The values observed are surprisingly large. To compare them with optical model calculations, we have assumed $\Delta(3,3)$ dominance and multiplied the charge exchange cross section by 6 to obtain the estimated total quasi-free scattering cross section. In Table II, several pertinent optical model results are given for comparison. Stricker, McManus, and Carr⁵ estimate a quasi-free cross section at 50 MeV which appears to be smaller than the value estimated from the present experimental data. Liu and Shakin⁶ give estimates of the reaction cross section. The estimates of total pion scattering in Table I appear disproportionately large compared to their values, in view of the results of other experiments⁷ that pion absorption is a large part of the reaction cross section in this region. The discrepancy between experiment and calculation is evident. The results suggest that the simple assumption of $\Delta(3,3)$ dominance is not valid and more detailed calculations are in order.

Analysis of the complete body of data is continuing and we expect to have a comprehensive base of data to describe the broad outline of charge exchange scattering in the near future.

TABLE I
**MEASURED TOTAL SINGLE PION CHARGE EXCHANGE CROSS SECTIONS AND ESTIMATED TOTAL
 INELASTIC SCATTERING CROSS SECTIONS AT 100 MeV**

<u>Target</u>	<u>T(π^+) MeV</u>	<u>$\sigma(\pi^+, \pi^0)$ mb</u>	<u>$\sigma(\pi^+, \pi^{+'})^a$ + $\sigma(\pi^+, \pi^0)$ mb</u>
$^{16}_0\text{O}$	50	21	126
	100	66	396
	150	79	474
$^{58}_{\text{Ni}}$	100	104	624

^aCalculated by assuming $\Delta(3,3)$ dominance, i.e. $\sigma(\pi, \pi') = 56(\pi^+, \pi^0)$.

TABLE II
QUASI-FREE AND TOTAL REACTION CROSS SECTIONS FROM OPTICAL MODEL CALCULATIONS

<u>Target</u>	<u>T(π^+) (MeV)</u>	<u>$\sigma_T^{q.e.}(\pi, \pi')$ (mb)</u>	<u>σ_{react} (mb)</u>
$^{16}_0\text{O}$	50 ^a	45	201
$^{16}_0\text{O}$	40 ^b		132
	79 ^b		376
	114 ^b		492

^aReference 5.

^bReference 6.

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