Inclusive pion double charge exchange on $^{16}$O above the delta resonance

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The forward inclusive pion double charge exchange reaction, $^{16}$O($\pi^-, \pi^+)$X, at $T_0 =$ 0.50 and 0.75 GeV has been studied in the kinematic region where an additional pion production is forbidden by energy-momentum conservation. The experiment was performed with the SKS spectrometer at KEK PS. The measured ratio of double charge exchange cross-section for these energies $⟨d\sigma(0.50 \text{ GeV})/dΩ⟩ / ⟨d\sigma(0.75 \text{ GeV})/dΩ⟩$ = $1.7 \pm 0.2$, disagrees with the value of 7.2 predicted within the conventional sequential single charge exchange mechanism. Possible reasons for the disagreement are discussed in connection with the Glauber inelastic rescatterings.

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The pion double charge exchange reaction (DCX) is a good testing ground for probing nucleon-nucleon correlations in a nucleus due to its two nucleon nature. In the past this reaction was extensively studied at LAMPF energies $T_0 \leq 0.50 \text{ GeV}$ and it was shown that the DCX can be described reasonably well in the framework of sequential single charge exchange (SSCX) models. In these models, pion DCX is explained by two successive single charge exchanges with a real neutral pion in an intermediate state (Fig. 1(a), $H^0 = \pi^0$). The SSCX mechanism predicts rapid decrease of the forward DCX cross sections for pion energies above 0.5 GeV. For this reason high-energy DCX was suggested (see, e.g. Ref. [2, 3]) as a probe of the short-range nucleon-nucleon correlations in a nucleus and new mechanisms of pion propagation in the nuclear medium.

Pion DCX above 0.5 GeV can be studied experimentally only in the narrow kinematic region of outgoing pion momenta near the high energy end point where production of additional pions is forbidden by the energy-momentum conservation. This requires both a high intensity pion beam and a good spectrometer system in the 1 GeV/c region. We studied the process

$$\pi^- + ^{16}\text{O} \rightarrow \pi^+ + X \quad (1)$$

using superconducting kaon spectrometer (SKS) at KEK 12-GeV PS sharing the apparatus of the E438 experiment which measured the $(\pi^- , K^+)$ reaction [5]. In this paper we give a brief description of the experimental setup, data taking and analysis procedures which are discussed in detail in Ref. [5].

Negative pions of kinetic energy $T_0 =$ 0.50 and 0.75 GeV with the beam flux of $(1 - 2) \times 10^6$ pions per spill were delivered to the target at the K6 beamline. The beam spectrometer consisted of a $QQDQQ$ magnet system, four sets of the drift chambers with 24 layers of sense wire planes in total used for the momentum reconstruction and three trigger counters: a freon-gas Čerenkov counter (GC) and two sets of segmented scintillation counters $BH1$ and $BH2$. Beam particle, identified by the beam spectrometer, interacted in the 5-cm long $H_2O$ target. Positive particles emitted in the forward direction (the reaction angle was $\theta \leq 15^\circ$) in the process

$$\pi^- + A \rightarrow (e^+, \pi^+, p) + X \quad (2)$$

were measured with the SKS spectrometer consisting of a superconducting dipole magnet, four sets of the drift chambers with 22 layers of sense wire planes in total and several trigger counters: TOF wall and Lucite Čerenkov counter wall (LC) for proton suppression. Data were taken with a trigger $BH1 \times BH2 \times GC \times TOF \times LC$. The trigger rates varied from 60 to 400 per spill depending on the beam energy. At each beam energy two settings of the magnetic field ($I_{SKS} =$ 145 A and 175 A at $T_0 =$ 0.50 GeV and $I_{SKS} =$ 272 A and 320 A at

FIG. 1: Diagrams contributing to pion double charge exchange on a nucleus:
(a) sequential single charge exchange (SSCX) with $\pi^0$ in the intermediate state ($H^0 = \pi^0$) and
(b) inelastic Glauber rescatterings with two pions in the intermediate state ($H^0 = \pi^+\pi^- \mbox{ or } \pi^0\pi^0$).

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\( T_0 = 0.75 \text{ GeV} \) were used to cover the wider range of the outgoing pion energy \( T \). These pions have to be discriminated from protons and positrons. Time-of-flight measurement between \( BH2 \) and the TOF wall was used to reject protons.

The beam flux used and the numbers of selected events are given in the Table I. The events have passed the standard SKS cuts on the number of hits in the drift chambers, on the vertex position in the target, etc. The selection procedure is described in detail in Ref. [6]. We used additional cut on the reaction angle \( 4^\circ \leq \theta \leq 6^\circ \) which was applied to reduce the positron background as described below and to facilitate a comparison with the existing data [7, 8]. Apart from the total number of selected events, \( N_{\text{tot}} \), the numbers of events in energy ranges \( 0 \leq \Delta T = T_0 - T \leq 80(140) \text{ MeV} \), \( N_{80} \) (\( N_{140} \)) are given.

### TABLE I: The numbers of selected events used for cross section calculations for different energy and SKS current settings.

| \( T_0, \text{ GeV} \) | \( I_{\text{SKS}}, \text{ A} \) | \( N_{80} \) | \( N_{\text{tot}} \) | \( N_{80} \) | \( N_{140} \) |
|---------------------|-------------------------|--------|-----------------|--------|-----------------|
| 0.5                 | 145                     | 7.2    | 1599            | 197    | 1033            |
| 0.5                 | 175                     | 15.7   | 1017            | 433    |                 |
| 0.75                | 272                     | 25.2   | 3710            | 362    | 1661            |
| 0.75                | 320                     | 32.6   | 4859            | 621    | 2449            |

Among the detected particles there is a sizable fraction of positrons which originate from two sources. Electrons contaminating the beam can radiate the photons, photon conversion in the target produces the positron. Positrons can also result from the single charge exchange \( \pi^- \to \pi^0 \) processes in the target followed by the \( \pi^0 \to \gamma \gamma \) decays and photon conversion or direct Dalitz decays of the produced \( \pi^0 \)'s.

Special run was devoted to study the positron background. An additional aerogel (\( n = 1.01 \)) Čerenkov counter (\( AEC \)) was placed downstream of the target. It was tested in the 150 MeV electron beam from the electron LINAC at Tohoku University. The signals from the \( GC \) and the \( AEC \) Čerenkov counters were measured and used off-line to separate pions from electrons/positrons. Such off-line analysis allowed to disentangle the following four reactions: \( (\pi^-, \pi^+), (e^-, \pi^+), (\pi^-, e^+) \) and \( (e^-, e^+) \) registered with the \( BH1 \times BH2 \times TOF \times LC \) trigger. Angular distributions for these four reactions are presented in Fig. 2 for \( T_0 = 0.75 \text{ GeV/c} \), as an example. The reaction \( (e^-, e^+) \) gives a sharp peak of the electromagnetic nature at \( 0^\circ \). For this reason, only the data in the angular region of \( 4^\circ \leq \theta \leq 6^\circ \) were used for further analysis. By solving the set of four linear equations the correction factor for the DCX cross section \( R = N(\pi^-, e^+)_{\text{true}}/(N(\pi^-, e^+)_{\text{true}} + N(\pi^-, \pi^+)_{\text{true}}) \) was calculated using the \( GC \) and the \( AEC \) efficiencies measured in the beam. For the kinematic region of pion DCX \( (\Delta T = T_0 - T \leq m_\pi \approx 140 \text{ MeV}) \) it was found to be \( 0.54 \pm 0.08 (0.35 \pm 0.06) \) for \( T_0 = 0.50 \) (0.75) GeV. Error in \( R \) is dominated by statistics in the chosen kinematic region.

We determined the differential cross section of the reaction \( (1) \) as a function of \( \Delta T \), corrected for ionization energy loss of initial and final pions in the target. The angular acceptance was calculated using Monte Carlo simulation which took into account the detector geometry, map of the magnetic field and the selection criteria applied in the analysis. The cross section was corrected for the muon contamination in the beam, detector efficiencies, efficiencies of the analysis and pion decays just in a similar way as it has been done in [6]. The product of the correction factors was calculated to be \( 0.320 \pm 0.005 \) for \( T_0 = 0.50 \text{ GeV} \) and \( 0.304 \pm 0.004 \) for \( T_0 = 0.75 \text{ GeV} \).

The positron background was taken into account using the \( R \) value which within the experimental errors did not depend on \( \Delta T \). To calibrate the \( \Delta T \) scale and energy resolution we used \( \Sigma^- \) hyperon peak reconstructed in the reaction \( \pi^- p \to K^+ \Sigma^- \) on the CH2 target and found the energy resolution to be less than 3 MeV (FWHM) (see [3, 4]). The systematic errors (without the uncertainty in the \( R \) value) which include the uncertainty of \( 10\% \) scale are also shown in the figures: solid and dashed curves.
At the calculation is based on the far extrapolation of the pion production cross section in this energy region and rise of the cross section above \( \Delta T \), the cascade type calculation does not explain correctly the reason for that is not yet understood. At \( \Delta T \) systematically lower than the data from LAMPF, the data from \[9\] of the anomalous energy dependence of inclusive pion production \( \pi^-+^{16}\text{O}\to\pi^-+\text{X} \). For \( \Delta T \) below 140 MeV this process is forbidden by the energy-momentum conservation. The cascade type calculation does not explain correctly the rise of the cross section above \( \Delta T \simeq 140 \) MeV. This is not surprising as there are no direct measurements of the pion production cross section in this energy region and the calculation is based on the far extrapolation of the existing data. At \( T_0 = 0.50 \) GeV our measurements are systematically lower than the data from LAMPF, the reason for that is not yet understood. At \( \Delta T \leq 0.12 \) GeV our results agree with the SSCX calculations with the core polarization (dashed curve). At \( T_0 = 0.75 \) GeV, however, the picture is somewhat different. Our results are in reasonable agreement with the previous measurements from ITEP, \[8\] which had larger errors and both sets of data are systematically above the SSCX predictions. The cross section \( \langle d\sigma/d\Omega \rangle_{\Delta T=0} \), integrated over the \( \Delta T \) range from 0 to 80 MeV, and \( \langle d\sigma/d\Omega \rangle_{\Delta T=140} \), integrated from 0 to 140 MeV, are presented in Table II. The errors quoted in the table include the statistical errors and the uncertainties coming from the determination of \( R \). The observed dependence suggests that either in this energy range we have a contribution of a new DCX mechanism or the charge exchange \( \pi N \) amplitude is modified in a nuclear medium.

TABLE II: DCX cross sections integrated over the \( \Delta T \) range from 0 to 80 MeV \( \langle d\sigma/d\Omega \rangle_{\Delta T=0} \) and from 0 to 140 MeV \( \langle d\sigma/d\Omega \rangle_{\Delta T=140} \) with their statistical errors and errors originating from the values of \( R \).

| \( T_0 \), GeV | \( \langle d\sigma/d\Omega \rangle_{\Delta T=0} \), \( \mu b/\text{sr} \) | \( \langle d\sigma/d\Omega \rangle_{\Delta T=140} \), \( \mu b/\text{sr} \) |
|-------------|----------------|----------------|
| 0.50        | 0.50 ± 0.75    | 0.50 ± 0.75    |
| 0.75        | 0.50 ± 0.75    | 0.50 ± 0.75    |

Also shown are the data of \[10\] at \( T_0 = 0.18, 0.21 \) and 0.24 GeV for \( \theta = 25^\circ \), the results of \[7\] for the reaction (3) and the results of \[8\] at 0.6 – 1.1 GeV.

FIG. 3: Differential cross section for \( \pi^-+^{16}\text{O}\to\pi^-+\text{X} \) at \( \theta = 4 - 6^\circ \) as a function of \( \Delta T = T_0 - T \) for different pion beam kinetic energies: (a) \( T_0 = 0.50 \) GeV; (b) \( T_0 = 0.75 \) GeV. Curves are described in the text.

FIG. 4: Energy dependence of the DCX cross section integrated over the \( \Delta T \) range from 0 to 80 MeV.

The ratios \( \langle d\sigma(0.5 \text{ GeV})/d\Omega \rangle_{\Delta T=0} / \langle d\sigma(0.75 \text{ GeV})/d\Omega \rangle_{\Delta T=0} = 1.1 \pm 0.2 \) and \( \langle d\sigma(0.5 \text{ GeV})/d\Omega \rangle_{\Delta T=140} / \langle d\sigma(0.75 \text{ GeV})/d\Omega \rangle_{\Delta T=140} = 1.7 \pm 0.2 \) are much smaller than SSCX predictions which are 7.5 and 7.2 for 0-80 MeV and 0-140 MeV \( \Delta T \) ranges respectively. Our results, based on large statistics, strongly support an observation of ITEP \[8\] of the anomalous energy dependence of inclusive pion DCX cross section in the beam energy range of 0.6 – 1.1 GeV. It was shown in Ref. \[11\] that the virtual multipion intermediate states, the so-called Glauber inelastic rescatterings (IR), seem to be important for the description of the inclusive DCX cross section at energies \( T_0 \gtrsim 0.6 \) GeV. In \[12\] the cross section of the reaction (1) was taken as the sum of two contributions, \[8\] one with an intermedi-
ate \( \pi^0 \) (SSCX, Fig. 1a), \( H^0 = \pi^0 \) and another one with an intermediate 2\( \pi \) state (IR mechanism, Fig. 1b), \( H^0 = \pi^+\pi^- \) and \( \pi^0\pi^0 \). The IR contribution was estimated in the framework of the Gribov-Glauber approach to DCX within the OPE model. The dotted and dashed curves in Figs. 1a and 1b correspond to the upper and the lower limits of the theoretical estimates of \([11]\). The dotted curve is much closer to the experimental data, especially for \( \langle \sigma(0.5 \text{ GeV})/d\Omega \rangle_{140} \), which represents a considerable improvement over the SSCX calculation.

It is worth mentioning here that IR is a new mechanism of pion propagation in a nuclear medium totally absent in cascade models where real pions and on-shell amplitudes are always used.

Modification of the charge exchange \( \pi N \) amplitude in a nuclear medium can be calculated using the approach developed in \([14]\) for \( \gamma N \) interactions. Within this approach modification of a \( \pi N \) or \( \gamma N \) amplitude in a nuclear medium is explained by the widening of the baryon isobars due to the new channels like \( NN^* \rightarrow NN \) being open in a nucleus. However the detailed calculations within this approach so far have not been performed.

In conclusion, we have measured the cross section of the inclusive DCX reaction \( \pi^- + { }^{16}\text{O} \rightarrow \pi^+ + X \) at two energies \( T_0 = 0.50 \) and 0.75 GeV and found the ratio of the measured cross sections \( \langle \sigma(0.5 \text{ GeV})/d\Omega \rangle_{140}/ \langle \sigma(0.75 \text{ GeV})/d\Omega \rangle_{140} = 1.7 \pm 0.2 \) to be much lower than the value of 7.2 predicted by the conventional SSCX mechanism. Evidently new mechanisms are needed to explain this discrepancy and the mechanism of inelastic rescatterings considered in \([11]\) seems to be one of the good candidates.

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