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

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The forward inclusive pion double charge exchange reaction, $^{16}\mathrm{O}(\pi^-, \pi^+)X$, 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 $\langle d\sigma(0.50\ \mathrm{GeV})/d\Omega\rangle / \langle d\sigma(0.75\ \mathrm{GeV})/d\Omega\rangle = 1.7 \pm 0.2$, 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 because of its two nucleon nature. In the past this reaction was extensively studied at LAMPF energies $T_0 \leqslant 0.50$ GeV [1] 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), $\mathrm{H}^0 = \pi^0$]. 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., Refs. [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

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

using superconducting kaon spectrometer (SKS) [4] at KEK 12-GeV PS sharing the apparatus of the E438 experiment that measured the (π^-,K$^+$) reaction [5]. In this article we give a brief description of the experimental setup, data taking, and analysis procedures discussed in detail in Ref. [6].

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, *BH*1 and *BH*2. Beam particles, 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 $\theta \leqslant 15^\circ$) 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 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 $BH1 \times BH2 \times \overline{GC} \times TOF \times LC$. The trigger rates varied from 60 to 400 per spill depending on the pion beam energy. At each beam energy two settings of the magnetic field ($I_{\mathrm{SKS}} = 145$ A and 175 A at $T_0 = 0.50$ GeV and $I_{\mathrm{SKS}} = 272$ A and 320 A at $T_0 = 0.75$ 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 *BH*2 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, and so on. The selection procedure is described in detail in Ref. [6]. We used additional cut on the reaction angle $4^\circ \leqslant \theta \leqslant 6^\circ$, 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_{tot}, the numbers of events in energy ranges $0 \leqslant \Delta T = T_0 - T \leqslant 80(140)$ MeV, N_{80} (N_{140}) are given.

Among the detected particles there is a sizable fraction of positrons that 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

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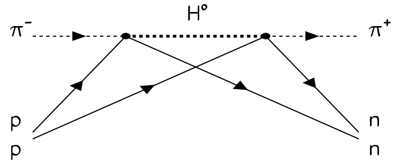

FIG. 1. Diagrams contributing to pion double charge exchange on a nucleus: (a) sequential single charge exchange (SSCX) with π^0 in the intermediate state ($\mathrm{H}^0 = \pi^0$) and (b) inelastic Glauber rescatterings with two pions in the intermediate state ($\mathrm{H}^0 = \pi^+\pi^-$ and $\pi^0\pi^0$).

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 π^0s.

A 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 us to disentangle the following four reactions: (π^-, π^+), (e^-, π^+), (π^-, 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 $T_0 = 0.75$ GeV, as an example. The reaction (e^-, e^+) gives a sharp peak of the electromagnetic nature at 0°. For this reason, only the data in the angular region of $4^\circ \leqslant \theta \leqslant 6^\circ$ were used for further analysis. By solving the set of four linear equations the correction factor for the DCX cross section $R = N(\pi^-, e^+)_{\mathrm{true}}/[N(\pi^-, e^+)_{\mathrm{true}} + N(\pi^-, \pi^+)_{\mathrm{true}}]$ was calculated using the *GC* and the *AEC* efficiencies measured in the beam. For the kinematic region of pion DCX ($\Delta T = T_0 - T \leqslant m_\pi \approx 140$ MeV) it was found to be 0.54 ± 0.08 (0.35 ± 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 ΔT, corrected for ionization energy loss of initial and final pions in the target. The angular acceptance was calculated using Monte Carlo simulation that 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 Ref. [6]. The product of the correction factors was calculated to be 0.320 ± 0.005 for $T_0 = 0.50$ GeV and 0.304 ± 0.004 for $T_0 = 0.75$ GeV. The positron background was taken into account using the

TABLE I. The numbers of selected events used for cross section calculations for different energy and SKS current settings. N_{π^-} is a beam flux in units of 10^9.

T_0, GeV	I_{SKS}, A	N_{π^-}	N_{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	7710	362	1661
0.75	320	32.6	4859	621	2449

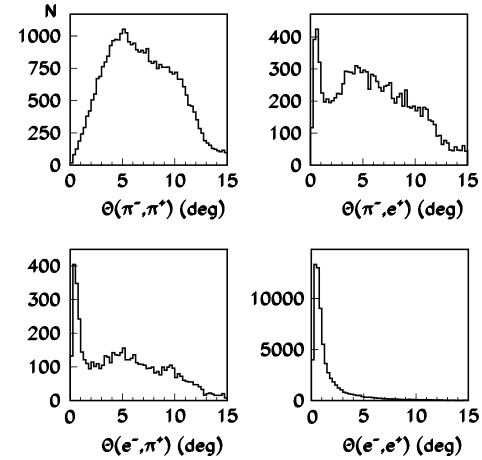

FIG. 2. The angular distributions for the reactions (π^-, π^+), (e^-, π^+), (π^-, e^+), and (e^-, e^+) at $T_0 = 0.75$ GeV and $I_{\mathrm{SKS}} = 320$ A as an example. Detection efficiencies of *GC* and *AEC* measured in the beam were $\epsilon^{GC} = 0.94$ (0.095) and $\epsilon^{AEC} = 0.87$ (0.13) for electrons (pions).

R value that within the experimental errors did not depend on ΔT. To calibrate the ΔT scale and energy resolution we used Σ^- hyperon peak reconstructed in the reaction $\pi^- p \to K^+\Sigma^-$ on the CH_2 target and found the energy resolution to be less than 3 MeV (FWHM) (see Refs. [5,6]). The systematic errors (without the uncertainty in the R value) that include the uncertainty of ΔT-scale calibration are estimated to be less than 10%.

The differential cross section of the reaction (1) for $4^\circ \leqslant \theta \leqslant 6^\circ$ at $T_0 = 0.50$ and 0.75 GeV calculated for two settings of the magnetic field at each energy is shown in Fig. 3

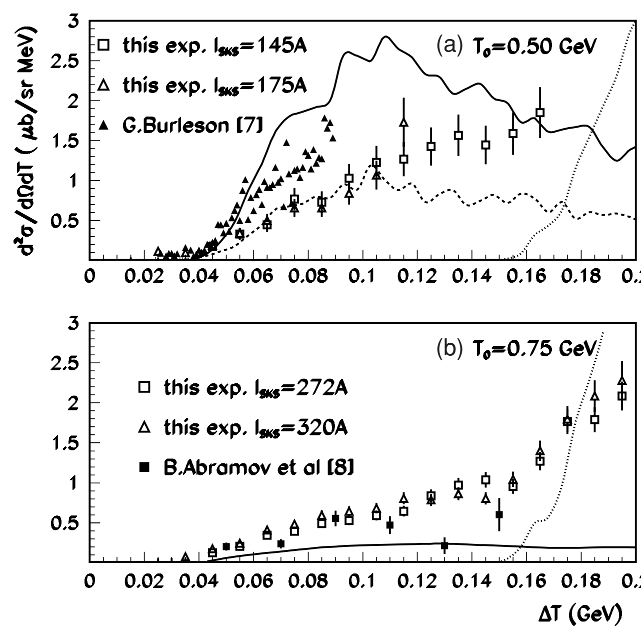

FIG. 3. Differential cross section for $\pi^- + {}^{16}\mathrm{O} \to \pi^+ + X$ at $\theta = 4$–6° as a function of $\Delta T = T_0 - T$ for different pion beam kinetic energies : (a) $T_0 = 0.50$ GeV; (b) $T_0 = 0.75$ GeV. Curves are described in the text.

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

	$\langle d\sigma/d\Omega\rangle_{80}$, $\mu b/sr$		$\langle d\sigma/d\Omega\rangle_{140}$, $\mu b/sr$	
T_0, GeV	0.50	0.75	0.50	0.75
$I_{SKS} = 145/272$ A	15.1 ± 3.5	12.7 ± 1.6	96.2 ± 17.5	53.2 ± 5.2
$I_{SKS} = 175/320$ A	16.6 ± 3.6	15.5 ± 1.8		59.0 ± 5.7
Averaged	15.9 ± 3.2	14.1 ± 1.5	96.2 ± 17.5	56.1 ± 5.4

where only statistical errors are given. The results for different SKS currents agree within the statistical errors in the overlap regions.

In Fig. 3 we compare our results to the available data from LAMPF for the reaction $\pi^+ + {}^{16}\text{O} \rightarrow \pi^- + X$ (3) at $T_0 = 0.50$ GeV (a) [7] and from ITEP at $T_0 = 0.75$ GeV (b) [8]. The results of the theoretical calculations are also shown in the figures: solid and dashed curves correspond to the calculations within SSCX model (see Refs. [8,9]) without and with a core polarization [3] and the dotted curve corresponds to the cascade-type calculation from [9]. The measured cross sections grow with ΔT. Figure 3(b) shows that the slope of the ΔT dependence changes around 150 MeV, which is near the threshold ($\Delta T \simeq 140$ MeV) of additional pion production $\pi^- + {}^{16}\text{O} \rightarrow \pi^+ + \pi^- + X$. For ΔT 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 $\Delta T \leqslant 0.12$ 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 $\langle d\sigma/d\Omega\rangle_{80}$, integrated over the ΔT from 0 to 80 MeV, and $\langle d\sigma/d\Omega\rangle_{140}$, 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. For the 80 MeV range they are comparable, whereas for the 140 MeV one the second source dominates. The measurements at different SKS currents are in good agreement and were averaged.

The energy dependence of the integrated cross sections $\langle d\sigma/d\Omega\rangle_{80}$ and $\langle d\sigma/d\Omega\rangle_{140}$ is shown in Figs. 4 and 5. 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.

The ratios $\langle d\sigma(0.5\text{ GeV})/d\Omega\rangle_{80}/\langle d\sigma(0.75\text{ GeV})/d\Omega\rangle_{80} = 1.1 \pm 0.2$ and $\langle d\sigma(0.5\text{ GeV})/d\Omega\rangle_{140}/\langle d\sigma(0.75\text{ GeV})/d\Omega\rangle_{140} = 1.7 \pm 0.2$ are much smaller than SSCX predictions, which are 7.5 and 7.2 for 0–80 MeV and 0–140 MeV ΔT 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. The observed dependence suggests that either in this energy range we have a contribution of a new DCX mechanism or the charge exchange πN amplitude is modified in a nuclear medium.

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 Ref. [12] the cross section of the reaction (1) was taken as the sum of two contributions, one with an intermediate π^0 [SSCX, Fig. 1(a), $\text{H}^0 = \pi^0$] and another one with an intermediate 2π state [IR mechanism, Fig. 1(b), $\text{H}^0 = \pi^+\pi^-$ and $\pi^0\pi^0$].[1] 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. 4 and 5 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 $\langle d\sigma/d\Omega\rangle_{140}$, 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

[1]Contributions from η^0 in diagram of Fig. 1 ($\text{H}^0 = \eta^0$) and from the mechanism of meson exchange currents appear to be small (see, respectively, Refs. [11,13]).

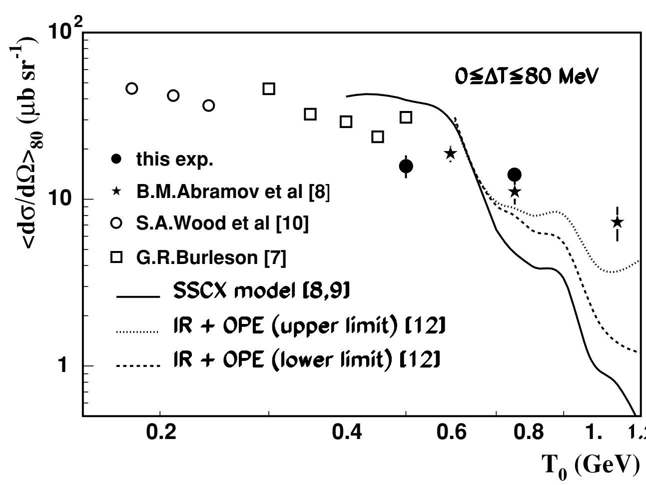

FIG. 4. Energy dependence of the DCX cross section integrated over the ΔT range from 0 to 80 MeV.

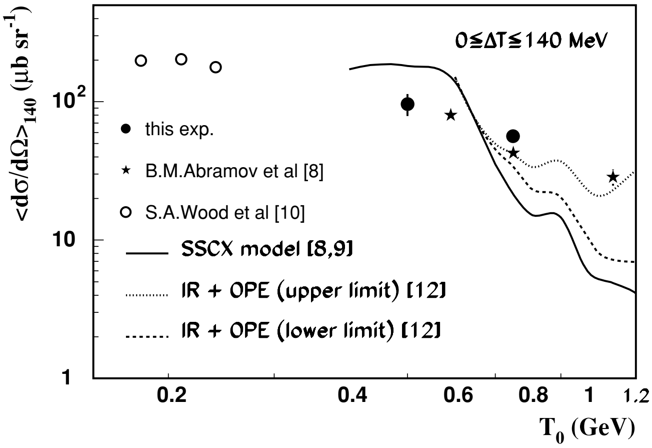

FIG. 5. Energy dependence of the DCX cross section integrated over the ΔT range from 0 to 140 MeV.

models where real pions and on-shell amplitudes are always used.

Modification of the charge exchange πN amplitude in a nuclear medium can be calculated using the approach developed in Ref. [14] for γN interactions. Within this approach modification of a πN or γN amplitude in a nuclear medium is explained by the widening of the baryon isobars because of the new channels such as $NN^{*\rightarrow} NN$ 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 $\pi^- + {}^{16}\mathrm{O} \rightarrow \pi^+ + X$ at two energies $T_0 = 0.50$ and 0.75 GeV and found the ratio of the measured cross sections $\langle d\sigma(0.5\ \mathrm{GeV})/d\Omega\rangle_{140}/\langle d\sigma(0.75\ \mathrm{GeV})/d\Omega\rangle_{140} = 1.7 \pm 0.2$ 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 Ref. [11] seems to be one of the good candidates.

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