Proposal of Experiment

Pion double charge exchange on oxygen at J-PARC

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Abstract

We propose to measure pion double charge exchange (DCX) cross sections on oxygen to investigate mechanisms of DCX at high energy. The Sks Plus Spectrometer has a unique possibility for detailed study of DCX in the most interesting energy range due to high intensity beams, available at J-PARC, very high momentum resolution, sufficient for observation of double isobar analoge transitions in nuclei and wide momentum acceptance, which is necessary for the inclusive DCX study. Above LAMPF energies these two processes are theoretically expected to be governed by different mechanisms of the "elastic" (with π^0 intermediate state) and "inelastic" (with $\pi\pi$ intermediate state) two sequential pion-nucleon interactions. Exclusive DCX reactions, as predicted by the conventional mechanism equivalent to the Glauber model with the "elastic" intermediate state (π^0), rapidly drop above 0.55 GeV. Meanwhile, inclusive processes have relatively smooth energy dependence due to effects of "inelastic" (mostly 2π) states. If observed, these different energy behaviors will be clear experimental evidence for inelastic intermediate transitions in hadron propagation through the nuclear matter.

The beam energy of 1 - 2 *GeV* is well suited for the experiment. Theoretically estimated decrease of the inclusive DCX cross section in this range is about 3 times within "inelastic" mechanism. The cross section for DIAS transition on $^{18}O(\pi^+,\pi^-)^{18}Ne$ is expected on the level of $10^{-2}\mu$b/sr within "elastic" mechanism.

1 Motivation

For many years the pion double charge exchange (DCX) processes stay one of the most active research areas in pion physics giving an important information [1,2] on nuclear structure and hadron dynamics as they involve interaction with at least two like nucleons of a nucleus. The standard DCX mechanism, equivalent to the Glauber model, corresponds to two sequential single charge exchanges (SSCX) of pion on nucleons of a nucleus with π^0 in the intermediate state (Fig.1(a)). This model gives a reasonable description of experimental data on DCX at kinetic energies of incident pions $T_0 \lesssim 0.5\ GeV$ and predicts [3-6] a strong decrease of a small angle DCX at higher energies due to fast decrease of a single charge exchange $\pi^{\mp} \rightarrow \pi^0$ amplitude. However, recent measurements of the inclusive DCX at energies 0.5 - 1.1 GeV performed at ITEP and KEK showed [7-8] [1] that the differential cross section of this process decreases with energy rather slowly and exceeds the theoretical prediction [9] at the highest energy by an order of magnitude. Thus other mechanisms of DCX are needed to explain the observed energy dependence.

The theoretical analysis [10] of the phenomenon has shown that the Glauber inelastic rescatterings (IR) of the type shown in Fig.1 (b) give an important contribution to the cross section of inclusive DCX at energies $T_0 > 0.6\ GeV$ and allow to understand the experimentally observed pattern of the energy dependence for this reaction. The Gribov formalism of quantum field theory [11] for a description of inelastic rescatterings on nuclei was used. In this approach a pion, propagating inside a nucleus, spends some time in a form of multipion state. It is known that the inelastic corrections to the Glauber model for hadron scattering on nuclei are important only at high energies, $E_0 \gtrsim 5\ GeV$. They are not very large and are approximately equal $\sim 20 \div 30\%$ of elastic correction [12-14], i.e. on the level of a few % of total cross section (that is important for agreement with experiment). It is interesting that in the DCX case inelastic rescatterings can dominate already at much smaller energies $T_0 \gtrsim 1\ GeV$. It is worth to mention here that this mechanism is out of scope of intranuclear cascade models. For an exclusive DCX the role of IR is unclear and has to be checked experimentally.

Let us note, that DCX kinematical region of kinetic energy transfer, $0 \leq \Delta T \leq m_\pi$, covers the exclusive case at $\Delta T \approx 0$ as well as maximally inclusive one at $\Delta T = 140\ MeV$. So we can detect both channels simultaneously.

The goal of the proposed experiment is the *unique comparative measurement* of the *exclusive* and *inclusive* DCX cross sections at energies where the elastic $\pi^{\mp} \leftrightarrow \pi^0$ transition in each of πN vertices are beginning to be replaced by the inelastic IR mechanism of $\pi^{\mp} \leftrightarrow \pi^+ + \pi^-\ (\pi^0 + \pi^0)$ transitions (see Fig.2). If IR effect is found, this observation will be the *direct experimental evidence for the inelastic intermediate rescatterings in the pion-nucleus interactions.*

[1] This measurements were made for the special kinematical region, $0 \leq \Delta T \leq m_\pi$ ($\Delta T = T_0 - T$, where T is the kinetic energy of outgoing pion), where additional pion production is forbidden.

2 Current status of DCX study

2.1 Inclusive reaction

The inclusive DCX cross section has been measured in ITEP and ITEP/KEK experiments in the reaction $A(\pi^-,\pi^+)X$ for ^{16}O (also ^6Li, ^7Li and ^{12}C) nuclei at kinetic energies $T_0 = 0.5,\ 0.6,\ 0.75$ and $1.1\ GeV$ ($\langle\theta\rangle \approx 5^0$) [7,8]. At high energy the DCX mechanism study is possible only in the region $0 \leq \Delta T \leq m_\pi$ where production of an additional pion is kinematically forbidden. The results of our experiments [8] for ^{16}O nuclei are presented in Fig.3 together with the data [15] at lower energies. The curves were calculated within SSCX mechanism [7,9] (*solid*) and within SSCX mechanism with inelastic rescatterings (IR) added [10] (*dotted* and *dashed* for *upper* and *lower* limits; OPE model was used). The forward inclusive DCX cross sections (measured and calculated) are given in the table below.

$0 \leq \Delta T \leq$ *140 MeV*	*Experiment*	*SSCX [7,9]*	*SSCX+IR [10]*
T_0 = 0.5 GeV	$96 \pm 17\ \mu b/sr$[8]	$182\ \mu b/sr$	$182\ \mu b/sr$
T_0 = 0.6 GeV	$80 \pm 4\ \mu b/sr$[7]	$139\ \mu b/sr$	$155\ \mu b/sr$
T_0 = 0.75 GeV	$43 \pm 4\ \mu b/sr$[7] $56 \pm 5\ \mu b/sr$[8]	$25\ \mu b/sr$	$34 - 42\ \mu b/sr$
T_0 = 1.1 GeV	$29 \pm 4\ \mu b/sr$[7]	$5\ \mu b/sr$	$8 - 25 \mu b/sr$

In Fig.4 the inclusive pion spectrum for $T_0 = 0.6\ GeV$ calculated within SSCX model is shown as an example. It is seen that DCX can only be measured in the region where additional pion production is kinematically forbidden. For outgoing pions with lower momentum (i.e. higher ΔT) it is impossible in an inclusive measurement to discriminate DCX events from two pion production events which have much larger cross section.

2.2 Exclusive reactions

There are three sets of appropriate data at relatively high energy ($T_0 \approx 0.5$ GeV); all of them were obtained with the spectrometer LAS at LAMPF. Theoretical calculations for $^{18}O(\pi^+,\pi^-)^{18}Ne$ ($DIAS$) within Glauber model in SSCX mechanism were presented in [3,5]. Measured and calculated forward exclusive cross sections are as follows.

LAS data at $T_0 = 500$ MeV	$\sigma, \mu b/sr$
[16] $^{18}O(\pi^+,\pi^-)^{18}Ne(DIAS)$	2.7 ± 0.4
[17] $^{48}Ca(\pi^+,\pi^-)^{48}Ti(DIAS)$	3.0 ± 0.8
[18] $^{16}O(\pi^+,\pi^-)^{16}Ne(g.s)$	0.2 ± 0.1

Theory [5]: $^{18}O(\pi^+,\pi^-)^{18}Ne(DIAS)$
$\sigma \approx 4\ \mu b/sr$ at $T_0 = 550$ MeV
$\sigma \approx 0.7\ \mu b/sr$ at $T_0 = 650$ MeV
$\sigma \approx 0.4\ \mu b/sr$ at $T_0 = 750$ MeV
$\sigma \sim 10^{-2} \mu b/sr$ at $T_0 =$ 1–1.4 GeV

3 Experimental requirements

The proposed experiment will use the Sks Plus Spectrometer [19] in the existing configuration of (K^-, K^+) experiment to measure inclusive DCX cross section at a single angle setting of $0^o \pm 15^o$ at $T_0 = 1.0 - 2.0$ GeV. The only additional important experimental requirement is a rejection of electrons in the beam and positrons upstream the target. Study of exclusive DCX in the reaction $^{18}O(\pi^+,\pi^-)^{18}Ne$ has to be done on positive pion beam. We hope that it will be possible to have π^+ beam at Sks Plus. For exclusive DCX the high momentum resolution is of crusial importance. It limits the target length to 2.5 cm or smaller. The cost and availability of ^{18}O can also limit the target length. In principal inclusive measurements on ^{16}O can be done with positive beam, but it can be decided later if exclusive channel will gain a support from the collaboration.

• *momentum resolution*

For exclusive reactions the best momentum resolution of Sks Plus (dp = $2.5 MeV/c$ (FWHM)) is needed, while for inclusive ones it is sufficient to have about 10 MeV/c.

• e/π *separation*

e^- contamination in the beam gives large background of e^+ after a target due to $e^- \rightarrow \gamma \rightarrow e^+$ conversion. In ITEP experiment e^+ flux after the target was an order of magnitude higher than the pion flux. So it is necessary to suppress electrons in the beam by two orders of magnitude with the help of a Cherenkov counter in the beam. Another Cherenkov counter after the target is also needed to eliminate e^+ produced in the target: $\pi^- \rightarrow \pi^0 \rightarrow \gamma \rightarrow e^+$. This background is not expected to be large.

• *π^+/p separation*

Background from protons can be easily eliminated with the time of flight wall with existing time resolution of $\sigma = 0.16$ ns. The pion-proton time difference is 3.3 ns at 1.5 GeV/c on the 5 m base. Non Gaussian tail in TOF spectrum has to be minimized.

• *energy resolution and target length*

Two sources contribute to energy resolution δE(FWHM) in energy excitation of final nucleus. The first one is the momentum resolution of the beam spectrometer dp = $0.6 MeV/c$ (FWHM) and of the Sks Plus itself which is equal to dp = $2.5 MeV$ (FWHM). The second one is fluctuations in energy losses in the target which can be approximated as 0.2 ΔE(FWHM) where ΔE is pion energy loss in the target. So expected δE(FWHM) is equal to 1.73, 2.45, 3.3, and 4.2 MeV for target lengths of 2.5, 5.0, 7.5, and 10.0 g/cm^2. For inclusive DCX the target length can be as long as 10 cm (H_2O). For exclusive DCX on ^{18}O the target length has not to be larger than 2.5 cm (H_2O).

• *needed beam time*

We shall use the following parameters to estimate beam time needed to detect DCX processes:
(1) beam intensity is equal to 5 x 10^6 pions per spill (1.32x10^{11}/day)[19] ,
(2) total efficiency is equal to 0.3 [8],
(3) angular acceptance is equal to 30 msr [19],
(4) H_2O target length is equal to 5 g/cm^2.

The yield N of inclusive DCX $^{16}O(\pi^-,\pi^+)X$
at T_0 = 1.1 GeV ($\langle \mathrm{d}\sigma/\mathrm{d}\Omega \rangle = 29\ \mu b/sr$)
is equal to

$$N = 13.2\text{x}10^{10}\text{x}(5\text{x}6.02/18)\text{x}10^{23}\text{x}29\text{x}10^{-30}\text{x}30\text{x}10^{-3}\text{x}0.3\text{=}5761 \text{ events/day.}$$

at T_0 = 1.5 GeV ($\langle \mathrm{d}\sigma/\mathrm{d}\Omega \rangle \approx 19.3\ \mu b/sr$)
is equal to

$$N = 13.2\text{x}10^{10}\text{x}(5\text{x}6.02/18)\text{x}10^{23}\text{x}19.3\text{x}10^{-30}\text{x}30\text{x}10^{-3}\text{x}0.3\text{=}3079 \text{ events/day.}$$

The yield N of exclusive DCX $^{18}O(\pi^+,\pi^-)^{18}Ne(g.s)$ at T_0 = 1.1 GeV ($\langle \mathrm{d}\sigma/\mathrm{d}\Omega \rangle \approx 0.02\ \mu b/sr$ within SSCX mechanism)
is equal to

$$N = 13.2\text{x}10^{10}\text{x}(5\text{x}6.02/20)\text{x}10^{23}\text{x}0.02\text{x}10^{-30}\text{x}30\text{x}10^{-3}\text{x}0.3\text{=}3.6 \text{ events/day.}$$

If inelastic Glauber rescatterings contribute also to exclusive DCX then this value can be almost an order of magnitude higher.

It is seen that three days are enough for inclusive DCX measurement at three energies with statistics of few thousand events. Additional ten days are needed to have 36 events of DIAS transition on ^{18}O.

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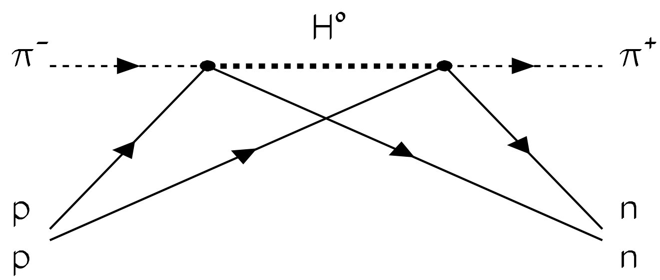


Figure 1: Diagrams contributing to pion double charge exchange on a nucleus:
(a) sequential single charge exchange (SSCX) with π^0 in the intermediate state ($\mathrm{H}^0 = \pi^0$) and
(b) inelastic Glauber rescatterings with two pions in the intermediate state ($\mathrm{H}^0 = \pi^+\pi^-$ and $\pi^0\pi^0$)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

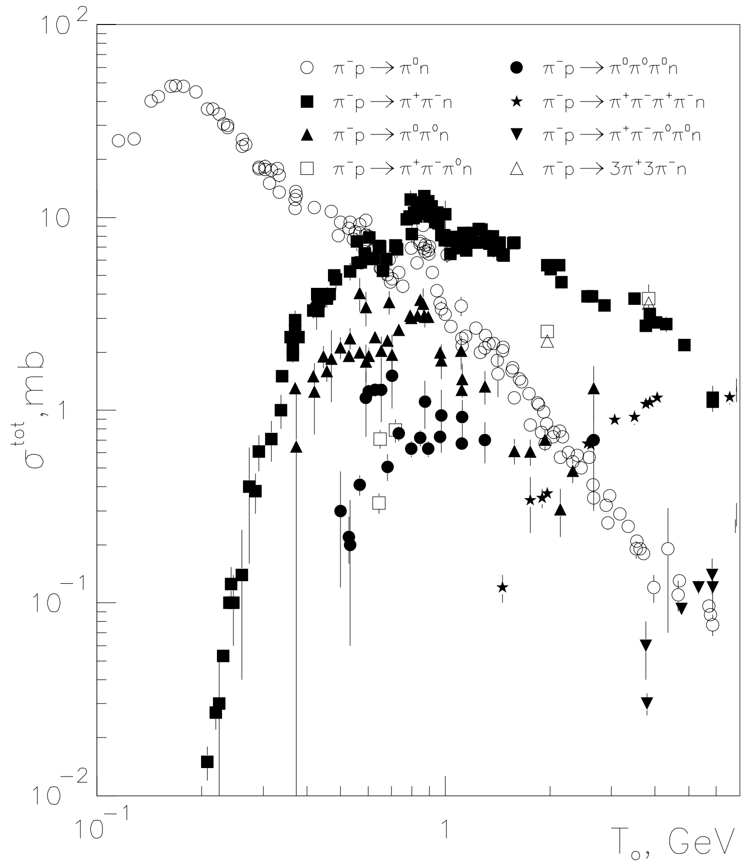


Fig.2. Experimental total cross sections (a compilation).

Figure 2:

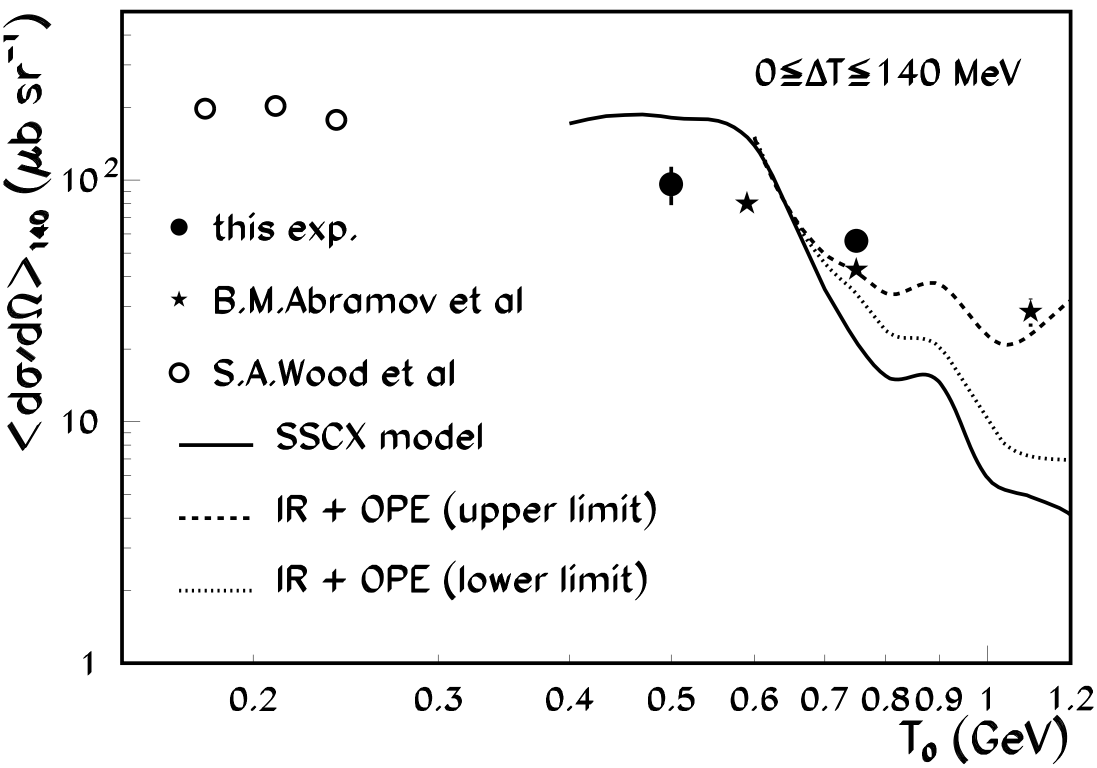
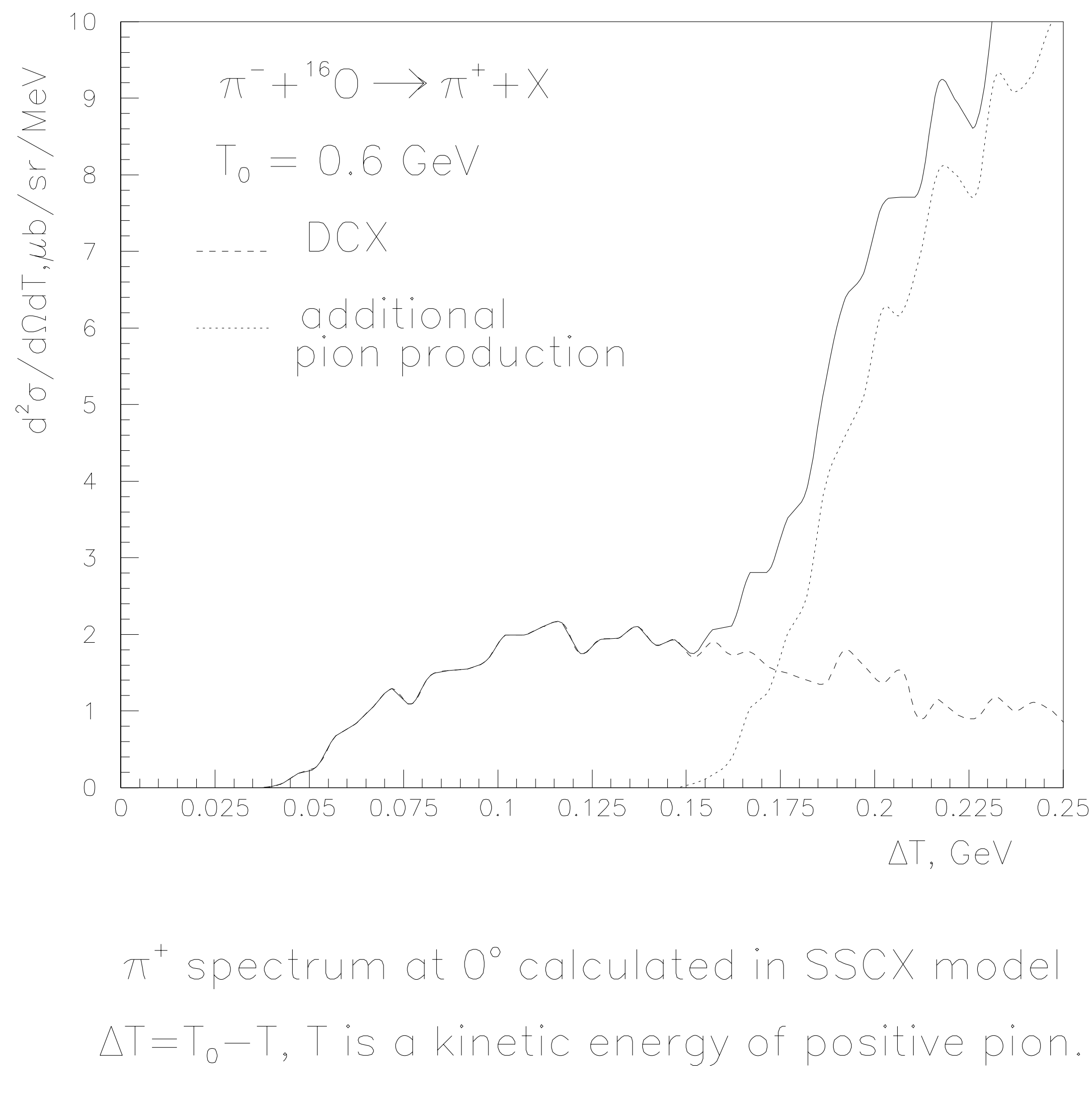


Figure 3: Energy dependence of the DCX cross section integrated over the ΔT range from 0 to 140 MeV.



$\pi^- + {}^{16}O \longrightarrow \pi^+ + X$
$T_0 = 0.6$ GeV
DCX
additional pion production
$d^2\sigma/d\Omega dT, \mu b/sr/MeV$
ΔT, GeV
0
1
2
3
4
5
6
7
8
9
10
0.025
0.05
0.075
0.1
0.125
0.15
0.175
0.2
0.225
0.25
π^+ spectrum at 0° calculated in SSCX model
$\Delta T = T_0 - T$, T is a kinetic energy of positive pion.

Figure 4: