P08 for J-PARC 50 GeV Proton Synchrotron

Pion double charge exchange on oxygen at J-PARC

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Proposed Experiment

- Beamline: K 1.8
- Beam energy: $T_0(\pi^-)$=1.1, 1.25, 1.5 GeV; $T_0(\pi^+)$=1.1 GeV
- Beam intensity: 5×10^6 π/spill

  Long Flat-Top time operation of 30 (50) GeV PS

- Set-up: K 1.8 Beam spectrometer, SKS+ spectrometer
- Targets and times: H_2O 5g/cm^2

$^{16}O(\pi^-,\pi^+)X$, <3 days,~10K events of forward inclusive DCX

By-product of P05 experiment

$^{18}O(\pi^+,\pi^-)^{18}Ne(g.s.)$, 10 days, ~30events of exclusive DCX

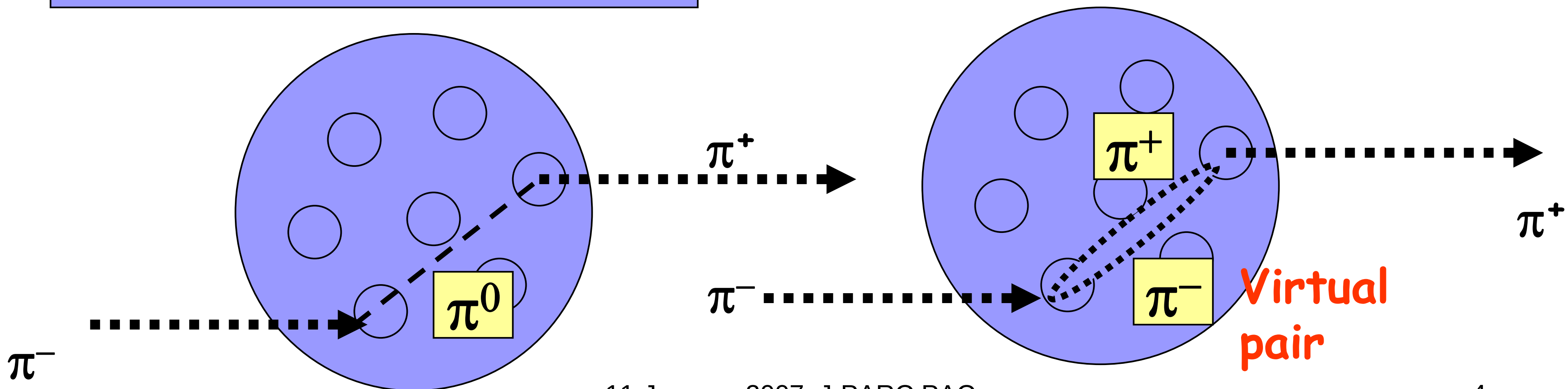
First observation at high energies

- Additional equipment: Cherenkov counter(s), ^{18}O target

Main goal of proposed experiment

Study of new mechanisms of pion propagation within a nucleus using pion double charge exchange reactions as a tool

Low energy <0.6 GeV; SSCX elastic rescattering	High energy >0.6 GeV; IR inelastic rescatterings



Pion double charge exchange on nucleus

Exclusive processes

$\pi^+ + A(Z,N) \rightarrow \pi^- + A'(Z+2,N-2)$

- double isobar analog states (DIAS)
- neutron halo of nuclei
- short range NN correlations
- exotic nuclei
- pion propagation inside nuclei

Inclusive processes

$\pi^{+/-} + A(Z,N) \rightarrow \pi^{-/+} + X$

- nonconventional DCX mechanisms
- inelastic Glauber rescatterings
- dibaryons
- modification of πN amplitude in nucl. medium
- meson exchange currents
- new mechanisms of pion propagation in nuclear media

Conventional mechanism at low energies:

two sequential single charge exchanges (SSCX)

$\pi^+ + A(Z,N) \rightarrow \pi^0 + A'(Z+1,N-1) \rightarrow \pi^- + A''(Z+2,N-2)$

Short DCX history (low energies)

1961 DCX as probe of short-range NN-correlations
[A.de Shalit, S.D.Drell, H.Lipkin, «Nucl.News», Weizmann Inst. Sci., Dec.61]

1963 First observation of DCX (in nuclear emulsion)
[JINR group, Yu.A.Batusov et al, ZhETF 46 (1964) 817]
Inclusive reaction $\pi^+ A \to \pi^- X$, T_0 = 80 MeV

1977 First transition to DIAS: $^{18}O(\pi^-, \pi^+)^{18}Ne$
T_0 = 139 MeV,LAMPF
[T.Marks et al, Phys. Rev. Lett. 38 (1977) 149]

High intensity pion beams, spectrometers with <1 MeV energy resolution: LAMPF, TRIUMF, PSI; T_0 < 0.5 GeV

Last reviews: H.Clement, Prog. Part. Nucl. Phys. 29 (1992) 175
M.B.Johnson and C.L.Morris, Ann. Rev. Nucl. Part. Sci. 43 (1993) 16

Short DCX history (high energies)

1980 **Exclusive reaction $\pi^+ + {}^4He \rightarrow \pi^- + 4p$**

Bubble chamber experiments (Nimrod), T_0 = 1.3-1.7 GeV

No DCX events in SSCX kinematics

1994 **Inclusive reaction $\pi^- A \rightarrow \pi^+ X$**

Magnet spectrometer with spark chambers (ITEP PS),
T_0 = 0.6, 0.75 and 1.1 GeV

Observation of anomalous slow decrease with energy
of forward DCX cross section on light nuclei

2002 **Inclusive reaction $\pi^- {}^{16}O \rightarrow \pi^+ X$**

SKS spectrometer with drift chambers (KEK PS),
T_0 = 0.5 and 0.75 GeV

Confirmation of slow decrease with energy
of forward DCX cross section on ^{16}O

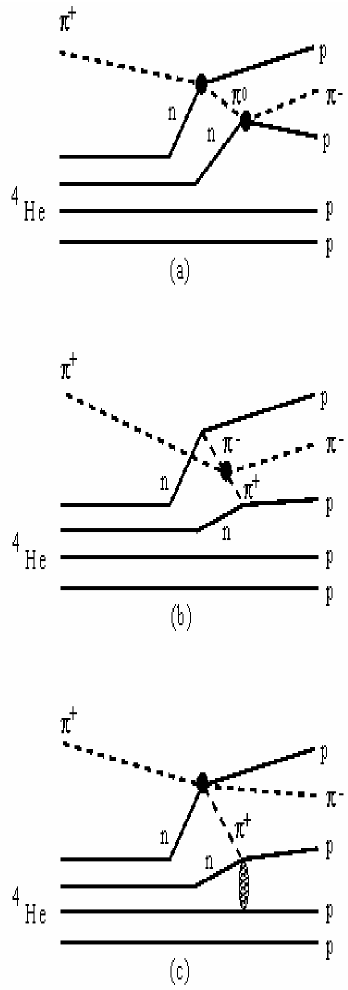
Motivation
for high energy pion DCX study

SSCX

- reasonably describes energy behavior of forward exclusive DCX at incident energies $T_\pi \equiv T_0 = 0.3\text{-}0.5$ GeV

- predicts rapid drop (with two dips) of pion DCX cross section at T_0=0.5-1.3GeV
  due to decrease of single charge exchange πN amplitude

[This effect is valid for exclusive and for inclusive DCX]



Unique testing ground for nonconventional mechanisms

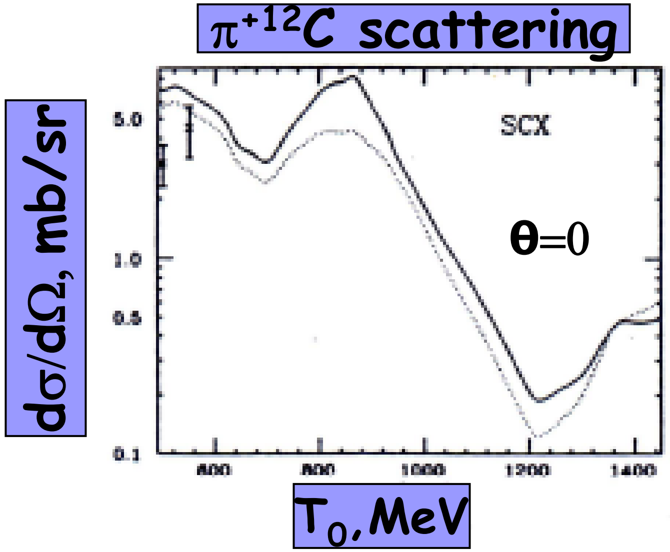
[D.Strottman (1988), E.Oset, and D.Strottman (1989), M.Arima, and R.Seki (1989) E.Oset,D.Strottman, H.Toki,J.Navarro (1993)]

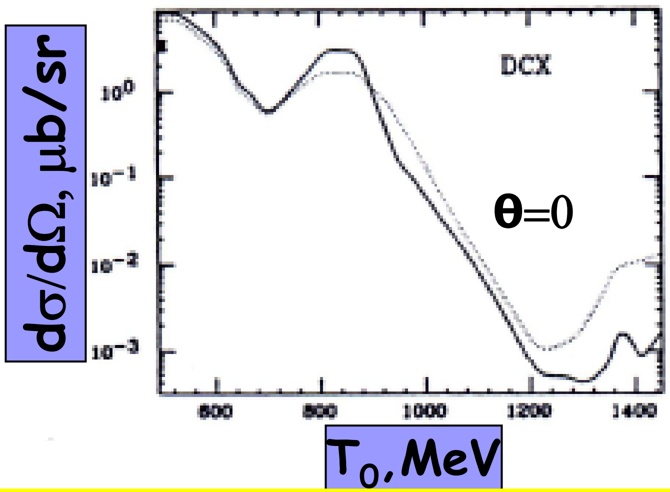
Program in DCX at SKS/KEK: not yet performed

[T. Nagae. (1990), O. Hashimoto (1990)]

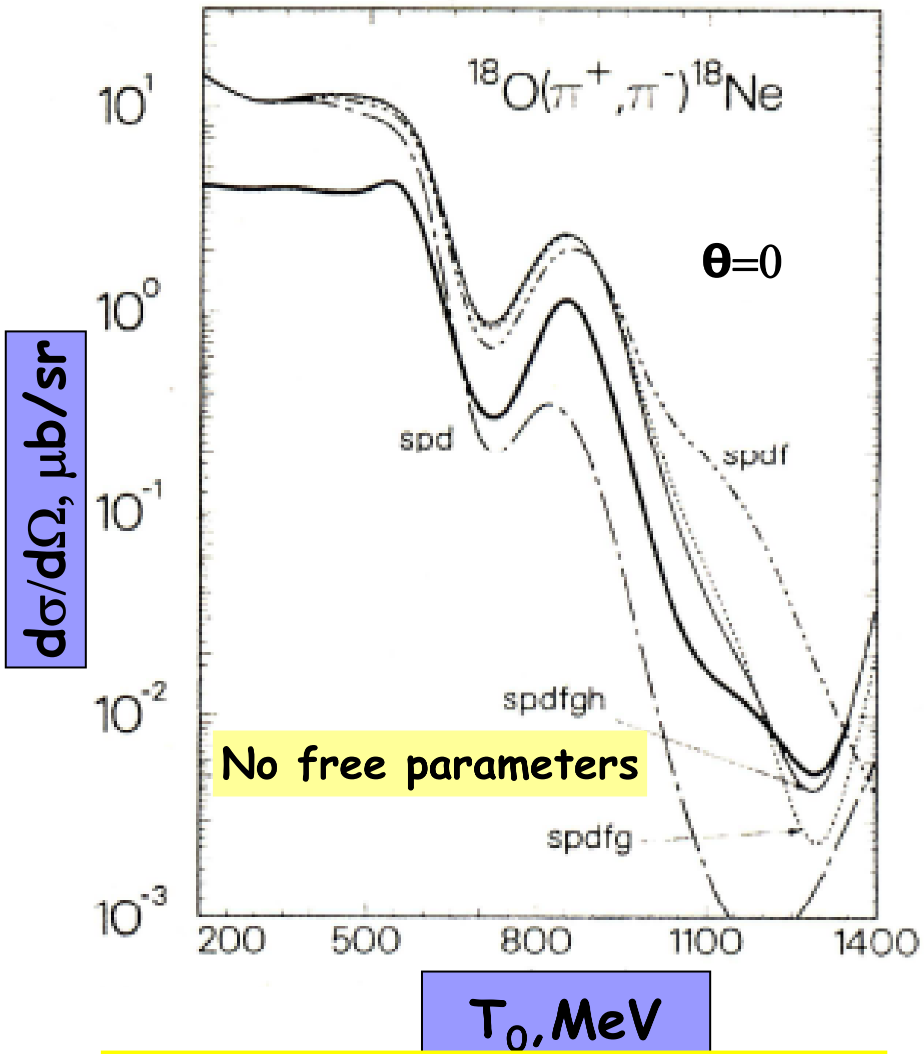
(a) SSCX mechanism
(b) meson exchange mechanism of Germond and Wilkin
(c) pn absorption mechanism of Jeanneret et al.

Motivation-2





M.Arima, R.Seki (1989)

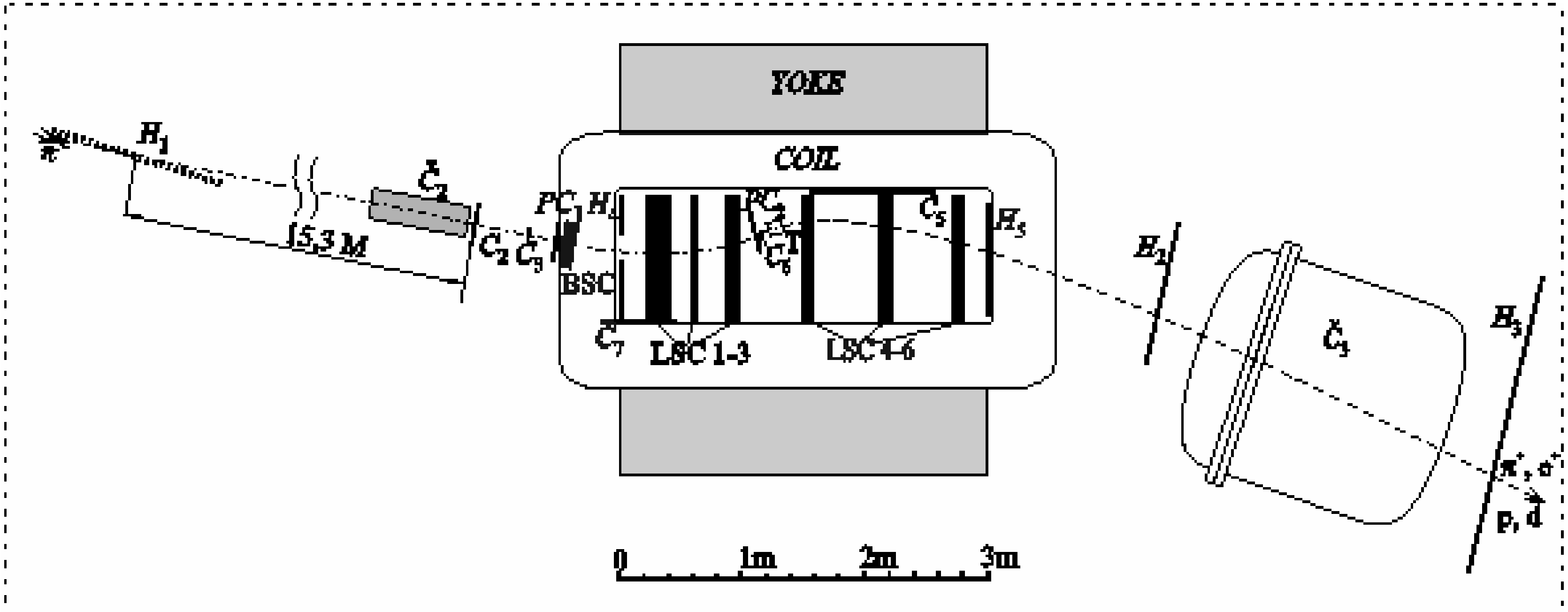


E.Oset, D.Strottman (1993)

ITEP inclusive DCX experiment: $\pi^- + {}^{16}O \rightarrow \pi^+ + X$

NP A723 (2003) 389

- 10 GeV PS ITEP, ~10^5 pions/spill
- 3-m spectrometer with spark chambers
- Incident energies: T_0 = 0.6, 0.75 and 1.1 GeV; $\theta < 14^o$
- Kinematical region: $0 < \Delta T < 140$ (or 80) MeV,
  $\Delta T = T_0 - T$, T is kinetic energy of outgoing pion
  (additional pion production is kinematically forbidden)
- ΔT scale calibration: $\pi^- + p \rightarrow p + \pi^-$; $\sigma(\Delta T)$ = 6-8 MeV



ITEP/KEK T459 experiment: $\pi^- + {}^{16}O \rightarrow \pi^+ + X$

PR C72 (2005) 037602

- 12 GeV PS KEK, K6 beam $(1\text{-}2)\cdot 10^6$ pions/spill
- Apparatus of $\pi^- \rightarrow K^+$ (E438) experiment:
- ΔT scale calibration: $\pi^- + p \rightarrow K^+ + \Sigma^-$
  $\sigma(\Delta T)$ = 2-3 MeV
  [H.Noumi et al. (2002), P.K.Saha et al. (2004)]
- Incident energies:
  T_0 = 0.50 GeV and 0.75 GeV; $\theta < 15^o$
- 5-cm long H_2O target

Kinematical region: $0 \leq \Delta T < 140$ (or 80) MeV

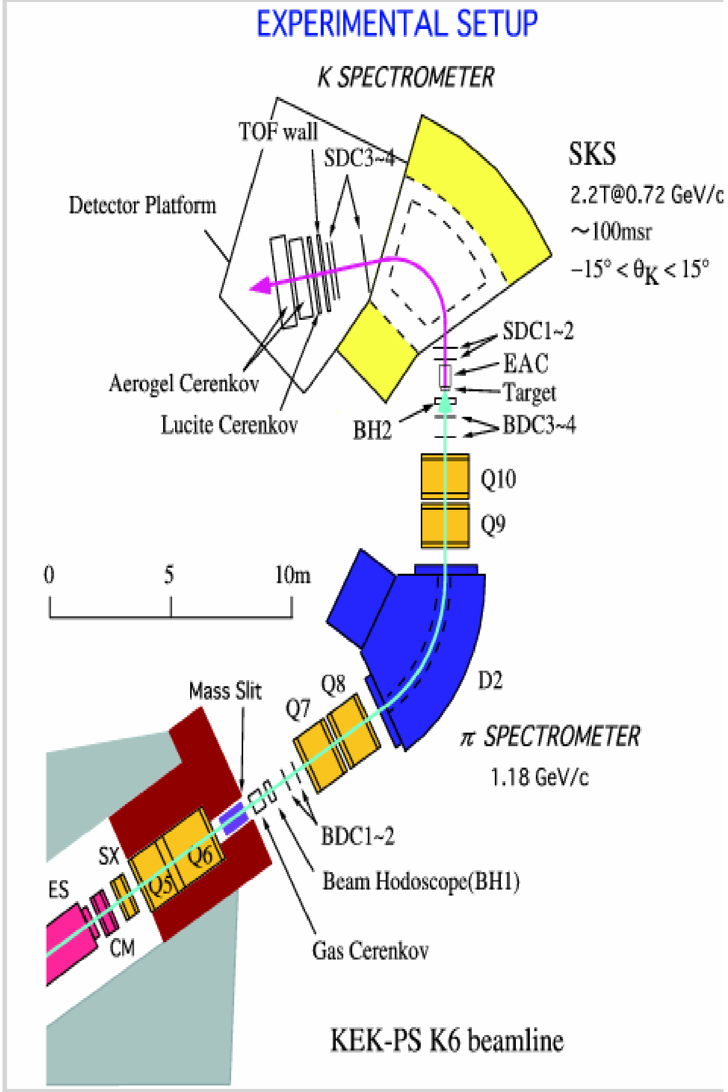
Trigger BH1 x BH2 x GC x TOF x LC:

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

Beam e^- suppression : GC

Proton background suppression: LC, TOF

Positron background study: special run with EAC



ITEP experiment *vs* KEK experiment

Experimental conditions

	ITEP	KEK
PS	10 GeV	12 GeV
T_0, GeV	0.59, 0.75, 1.10	0.50, 0.75
Beam intensity	~10^5 π^-/spill	~10^6 π^-/spill
θ, degrees	2-14	4-15
ΔT resolution	6-8 MeV	2-3 MeV
ΔT calibration	$\pi^- + p \rightarrow p + \pi^-$	$\pi^- + p \rightarrow K^+ + \Sigma^-$
main detectors	spark chambers	drift chambers
targets	H_2O, D_2O	H_2O
e^+ background	suppression with č	special run

ITEP experiment vs ITEP/KEK experiment

Backgrounds

Signal + background: $(e^- + \pi^-) + A \rightarrow (e^+ + \pi^+ + p,\ d) + X$

Sources of positrons (main background):

beam electrons: $e^- \rightarrow \gamma \rightarrow e^+$ in target

single charge exchange of beam pions: $\pi^- \rightarrow \pi^0 \rightarrow e^+$ in target

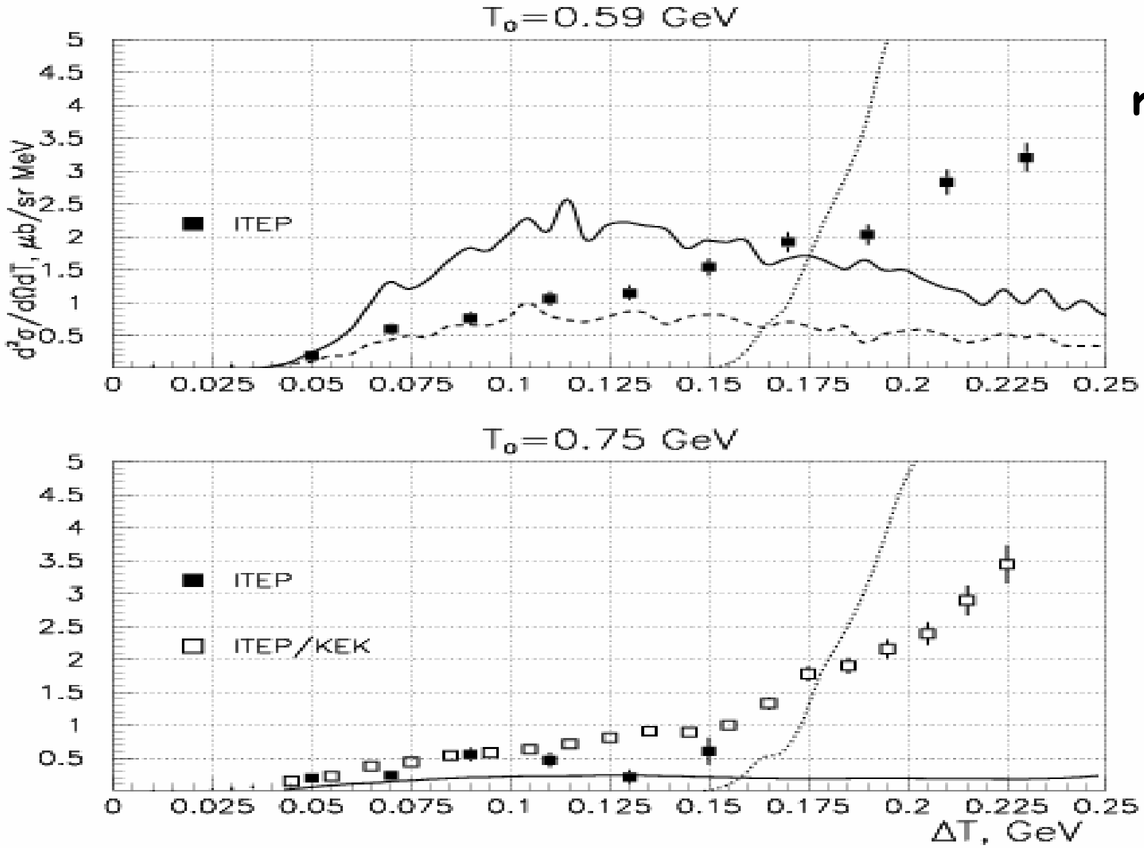
- p, d : suppression with TOF in both experiments
- e^- : suppression with Čerenkov counter + cut $\theta > 2^0$ (ITEP)
  suppression with cut GC and $\theta > 4^0$ (KEK)
- e^+ : suppression with Čerenkov counter (ITEP)
  cross section correction for e^+ background (KEK)

Positron background study (KEK):

special run with additional aerogel Čerenkov counter

π^+ energy spectra in reaction $\pi^- + {}^{16}O \rightarrow \pi^+ + X$

Spectra are integrated over
$0 < \Delta T = T_0 - T < 140$ or 80 MeV



Cascade type calculations:

SSCX mechanism
(solid curve),

SSCX + πN amplitude
modification in nuclear media
(dashed curve),

$\pi^- {}^{16}O \rightarrow \pi^+ \pi^- X$
(dotted curve)

[M.J.Vicente Vacas,
L.Alvarez-Ruso (2003)]

Integrated cross sections, μb/sr

$$\langle d\sigma/d\Omega\rangle_{140(80)} = \int_0^{140(80)} (d^2\sigma/d\Omega dT)\, d\Delta T$$

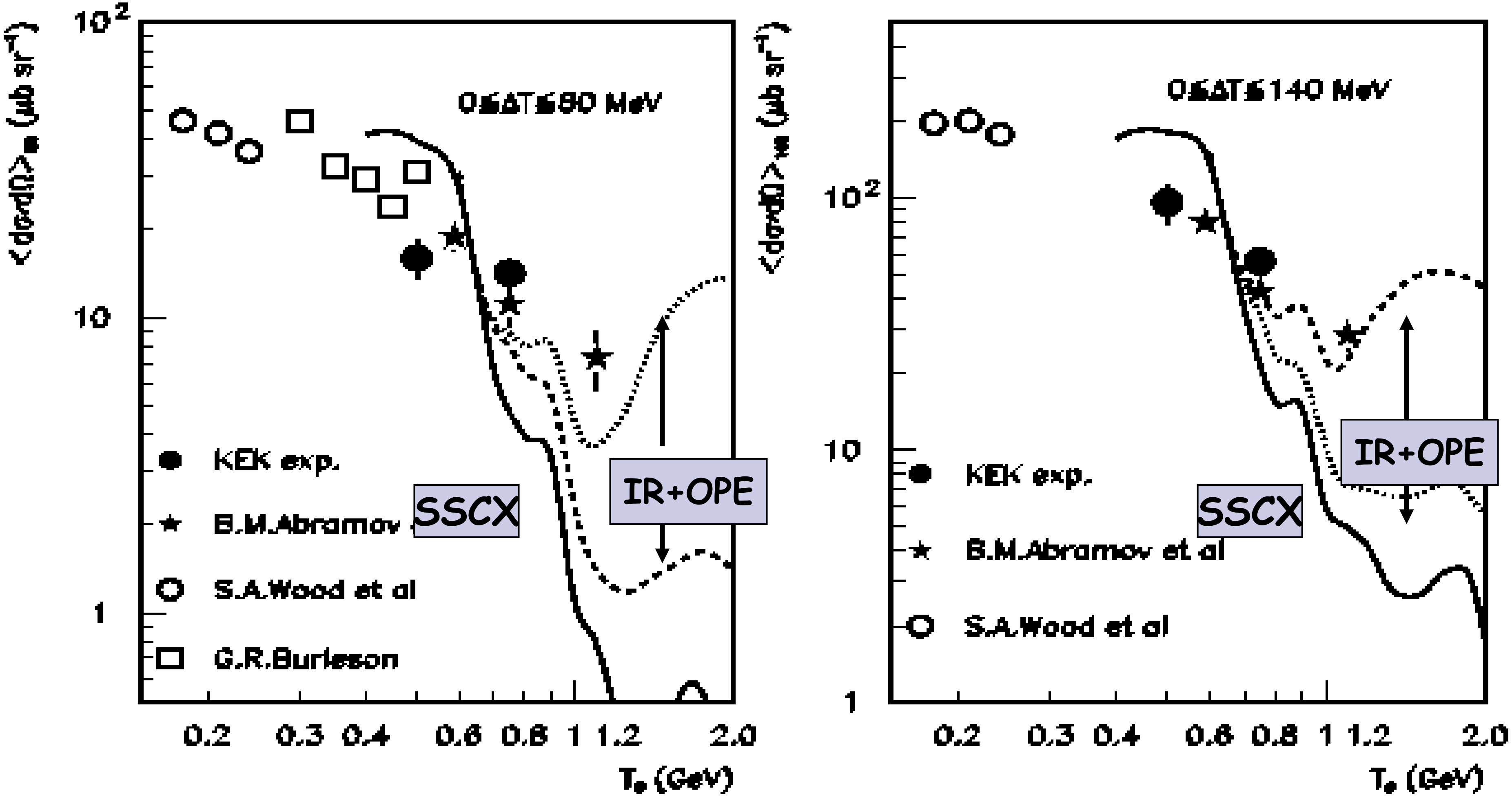
T_0, GeV		0.50	0.59	0.75	1.1
$\left(\frac{d\sigma}{d\Omega}\right)_{80}$	ITEP		18.8±2.8	11.1±2.1	7.3±1.8
	KEK	15.9±3.2		14.1±1.4	
$\left(\frac{d\sigma}{d\Omega}\right)_{140}$	ITEP		80.2±9.1	42.6±5.9	28.6±4.8
	KEK	96.2±17.6		56.1±5.4	

Statistical error: due to $N_{140(80)}$ (both exp.), ΔB (KEK)

Systematic error: ~10% due to ΔT scale, mainly (both exp.)
(Not shown in the table)

Energy dependence of inclusive DCX cross section

$\pi^- + {}^{16}O \rightarrow \pi^+_{forw} + X$



[IR + OPE: A.B.Kaidalov, and A.P.Krutenkova, 2001]

Energy dependence of inclusive DCX

$$\langle d\sigma/d\Omega \rangle_{140(80)} = \langle d\sigma/d\Omega \rangle_{140(80)}(\pi^0) + \langle d\sigma/d\Omega \rangle_{140(80)}(\pi\pi)$$

SSCX mechanism with real π^0
(elastic Glauber rescattering)

New mechanism with two pions
(inelastic Glauber rescatterings, IR)

For IR theoretical curves:

Upper limit: OPE model + experimental $\sigma(\pi \to 2\pi)$
Lower limit: OPE model

Current status of high energy DCX study

- Cross section of forward inclusive DCX reaction
  $\pi^- + {}^{16}O \rightarrow \pi^+ + X$ was measured:
  T_0 = 0.5, 0.59, 0.75 and 1.1 GeV (ITEP + ITEP/KEK)

- Inclusive σ(DCX) does NOT drop rapidly at $T_0 > 0.6$ GeV

↓

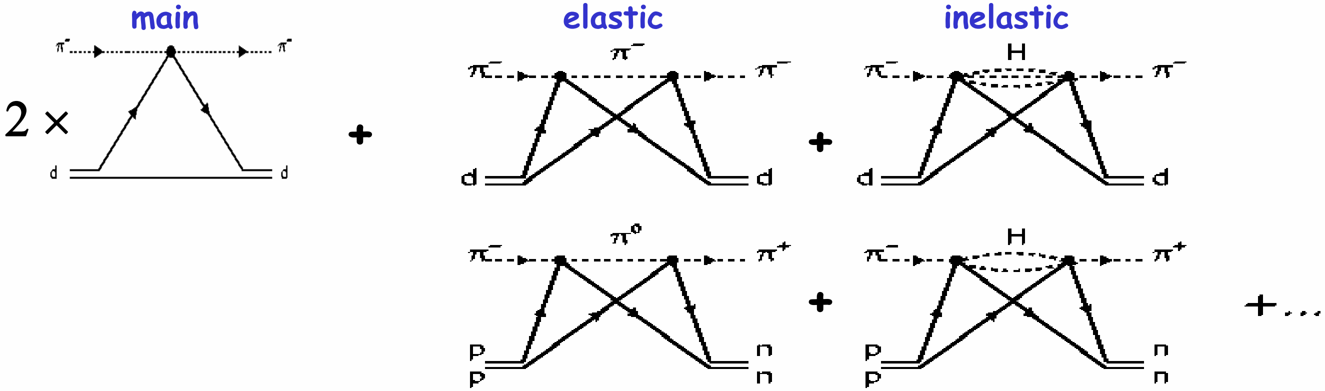
- At $T_0 > 0.6$ GeV SSCX mechanism with real π^0
  (elastic Glauber rescattering) does not dominate

- New mechanism with two pions in intermediate states
  (inelastic Glauber rescatterings: IR)
  seems to be a good candidate

Gribov formalism for pion nucleus scattering

Feynman diagrams for pion deuteron scattering:

Feynman diagrams for pion DCX scattering:



Gribov statements in framework of relativistic Quantum Field Theory

- Two "main" diagrams correspond to $\sigma_1 + \sigma_2$ in Glauber formula while "elastic" diagram gives Glauber screening (Glauber elastic rescattering)

- For higher energies, "inelastic" diagram with H = multipion state (Glauber inelastic rescattering) is substantial; thus Gribov obtains relativistic Glauber-type formula :

$$\sigma_d = 2\sigma_N - 2 \int dk^2 \rho(4k^2) (d\sigma_N/dk^2)$$

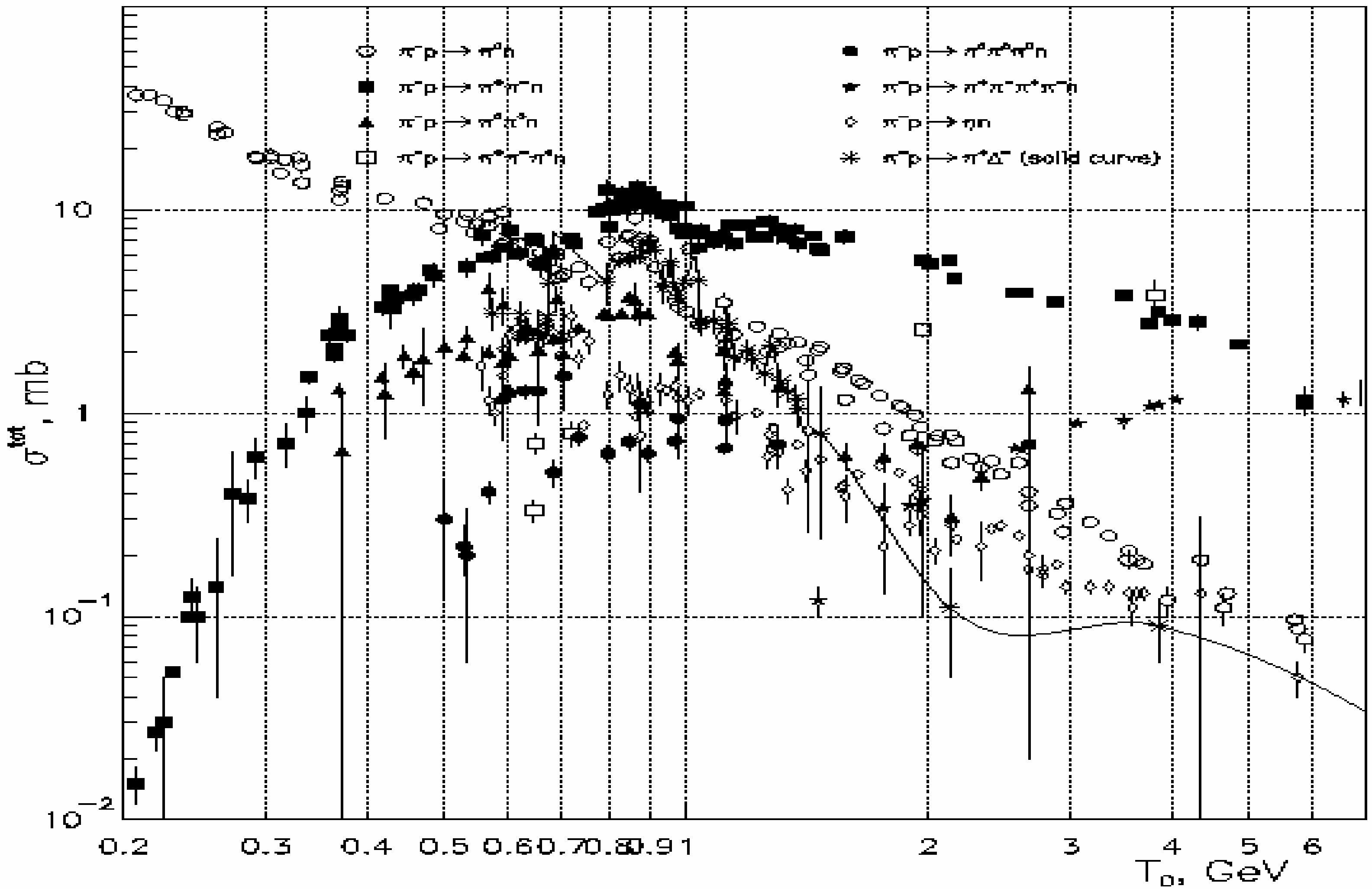
where k^2 is 3-momentum transfer to nucleon, squared, $\rho(4k^2)$ is charge form factor of deuteron, $d\sigma_N/dk^2$ is sum over all possible πN interactions (elastic and inelastic)

- For arbitrary nucleus, $d\sigma_N/dk^2$ is proportional to sum of total cross sections, squared:

$$d\sigma_N/d\Omega \propto \Sigma \iint dt\, dM^2 (d\sigma_{\pi\to H}/dtdM^2)^2$$

where t and M^2 are correspondingly invariant momentum transfer in both vertices and mass squared of intermediate state $H = 2\pi$ in "inelastic" diagram

Experimental data from V.Flaminio (compilation), 1983



Experimental total cross sections for reactions
$\pi^- + p \rightarrow H + n$ (H is meson state) and $\pi^- + p \rightarrow \pi^+ + \Delta$

Importance of IR study

Both proposed reactions imply start in first-hand study of inelastic Glauber rescatterings (IR).

- IR as relativistic QFT effects are now important in heavy ion collider physics (RHIC).
- Up to now IR are appeared only as per cent contribution to usual hadron-nucleus cross sections.
- Elastic rescattering gives 15–20% effect.
- IR are totally absent in cascade models.

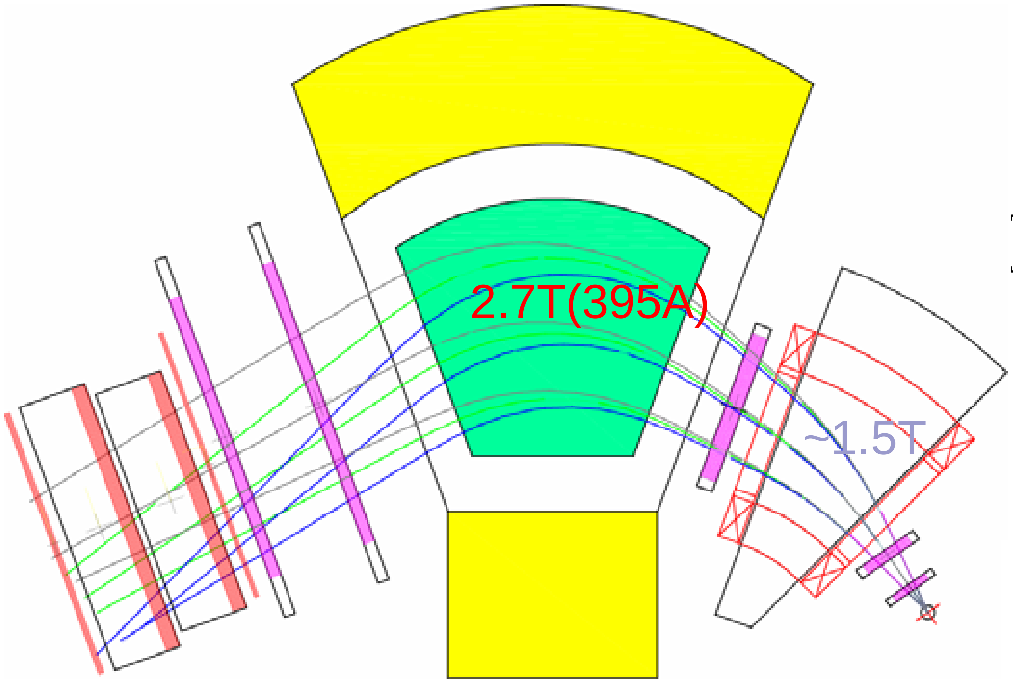
DCX is unique process where inelastic rescatterings seem to be main new mechanism at high energies

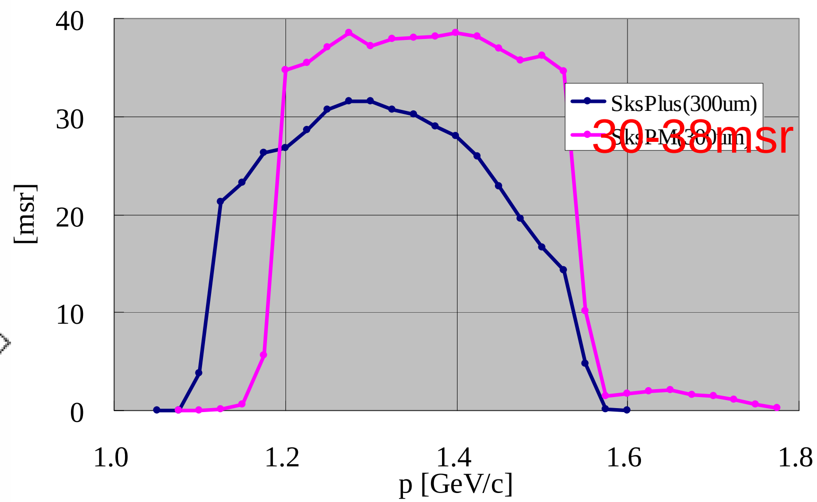
[Kaidalov and Krutenkova, Phys. Atom. Nucl.,1997; J.Phys.G, 2001]

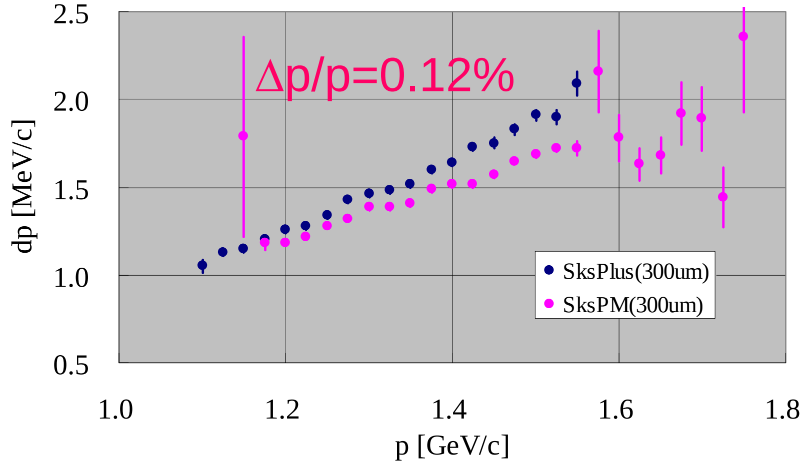
Experimental Method

- π^- beams @ K1.8 beamline
  - 1.25-1.65 GeV/c
- π^+ measured by SksPlus or SksMinus
  - 1-1.6 GeV/c
  - Inclusive: SksPlus(E05) or SksMinus(E13)
  - Exclusive: SksPlus due to high resolution

SksPlus for E05

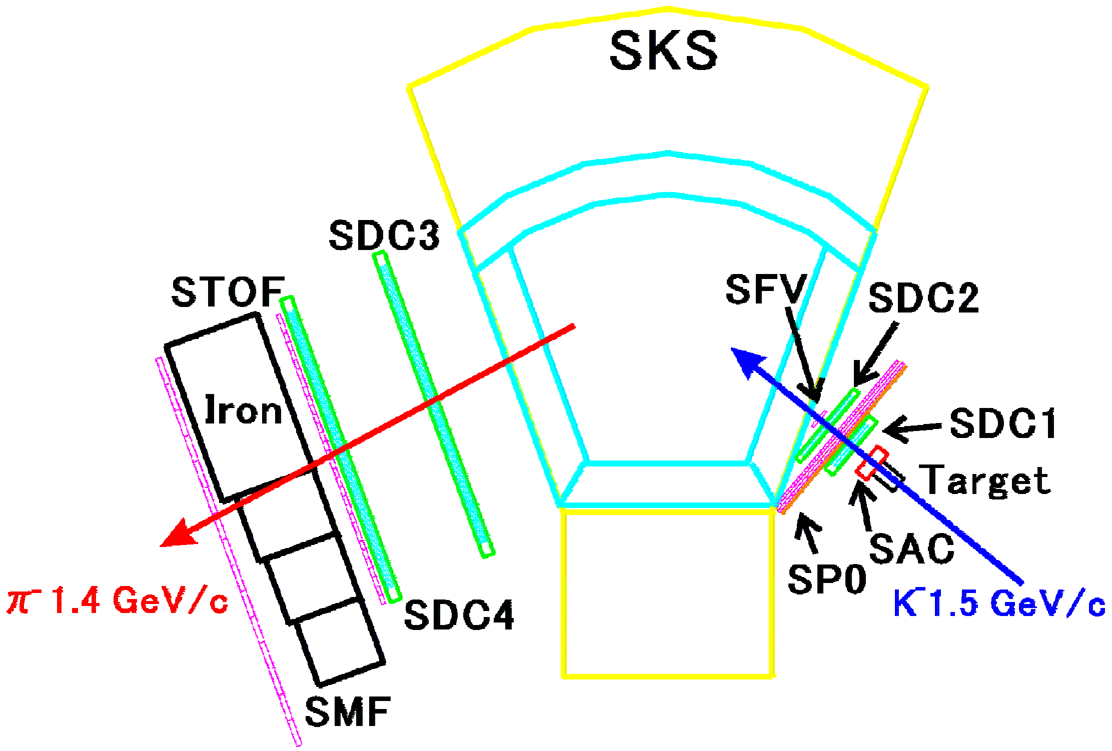


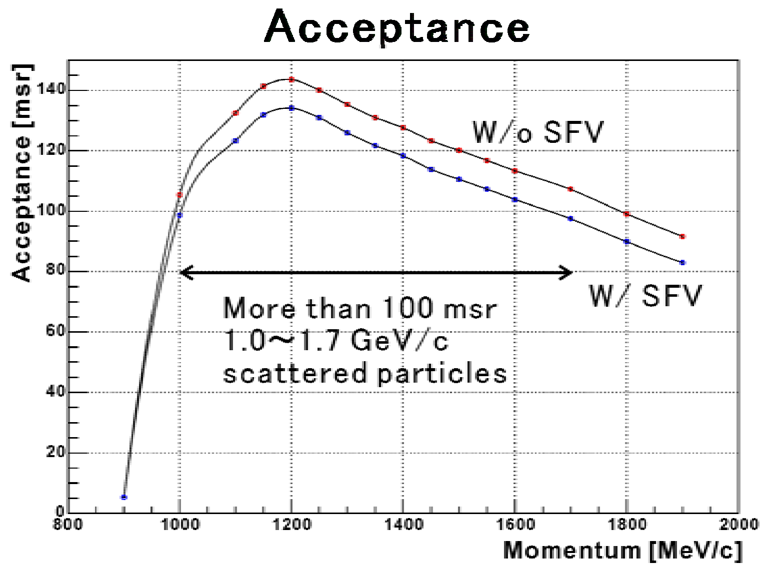


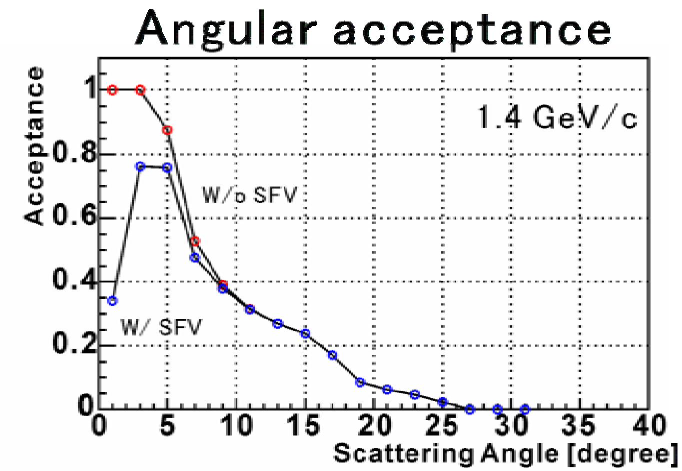


- 95° total bend
- ~7m flight path
- Δx=0.3 mm (RMS)

SksMinus for E13







Expected yield

$$N_{DCX} = N_{beam} \times N_{target} \times (d\sigma/d\Omega) \times \Delta\Omega \times f$$

Reaction $^{16}O(\pi^-, \pi^+)X$

$N(T_0=1.1GeV)=13.2\times10^{10}\times(5\times6.02/18)\times10^{23}\times$
$29\times10^{-30}\times30\times10^{-3}\times0.3=5.8K$ events/day

$N(T_0=1.5GeV)=13.2\times10^{10}\times(5\times6.02/18)\times10^{23}\times$
$19.3\times10^{-30}\times30\times10^{-3}\times0.3=3.1K$ events/day

Reaction $^{18}O(\pi^+, \pi^-)Ne(g.s.)$

$N(T_0=1.1GeV)=13.2\times10^{10}\times(5\times6.02/20)\times10^{23}\times$
$0.02\times10^{-30}\times30\times10^{-3}\times0.3=3.6$ events/day

Expected yield-2

$$N_{DCX} = N_{beam} \times N_{target} \times (d\sigma/d\Omega) \times \Delta\Omega \times f$$

$N_{beam}=5\times10^6$/spill (13.2×10^{10} /day)

Target length: 5g/cm^2 H_2O (^{16}O and ^{18}O)
total momentum resolution: ~4MeV FWHM
Beam: 0.6 MeV, SKS+: 2.5 MeV, target: 2.5 MeV

$(d\sigma/d\Omega)$=29μb/sr (19.3μb/sr) for 1.1GeV (1.5GeV)
$(d\sigma/d\Omega)$=0.02μb/sr for 1.1 GeV (exclusive)

Angular acceptance: 30 msr

Total efficiency: f=0.3

Summary

We propose to explore the dip region in energy dependence of pion double charge exchange reactions that is the unique testing ground for nonconventional mechanisms:

AS A PILOT STEP for inclusive reaction $^{16}O(\pi^-,\pi^+)X$
at T_0=1.1 GeV for reference,
1.5 GeV in the dip and
1.25 GeV between them, 3 days in total,
meaning that it is unique process where inelastic rescatterings dominate at GeV energies;

AS THE FINAL STEP for exclusive reaction $^{18}O(\pi^+,\pi^-)^{18}Ne(g.s.)$
at T_0=1.1 GeV 10 days (1 month?),
which will be the first observation of double isobaric analog state at high energy, meaning that J-PARC is the only place where it will be possible in the nearest future.

Possible update of Proposal for DCX

- **Study of inclusive DCX at energies 2-4 GeV**

  Starting from 2 GeV, OPE model predictions are reliable

- **A dependence from Li to Bi at 1.1 and 1.5 GeV**

  5 nuclei as a minimum; high statistics is not important

- **Exclusive DCX $^{14}C(\pi^+, \pi^-)^{14}O$ at 1.1 or 1.3 GeV**

  Predictions are similar to those for reaction on ^{18}O

  to be discussed with theoreticians