Neutrino interaction study in the K2K near detectors

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Outline

- Introduction
  - K2K experiment and Near detectors
- Current activities
  - Charged current analysis for $E_\nu$ spectrum measurement
  - Low $q^2$ deficit
  - Neutral current $\pi^0$ production
  - $M_A$ measurement
- On going analysis and future prospects
- Summary
K2K Experiment

KEK to Kamioka — first accelerator-based long (>100km) baseline neutrino experiment

Super-K (far detector)

L=250km
<Eν>~1.3GeV

Goal:
- Confirmation of νμ ↔ νx oscillation reported by Super-K atm-ν
- Search for νμ ↔ νe oscillation

Started in 1999

KEK
- ν beam line
- Beam monitor
- Near detectors

PRL 93, 051801
Neutrino beam-line

- Target/Horn: 12GeV PS
- Decay volume: (200m, π⁺ → µ⁺ + νµ)
- Near Detector: To Kamioka
- μ monitor
- νµ energy spectrum
  @ K2K near detector
  \( \langle E_\nu \rangle \sim 1.3 \text{GeV} \)
- 1.1μs spill/2.2s
  \( \sim 5.5 \times 10^{12} \) p/spill
- \( E_\nu (\text{GeV}) \)
Neutrino interaction ~1GeV

Charged current quasi-elastic scattering (CCQE)
Neutral current elastic scattering
CC/NC Single $\pi, (\eta, K)$ production via resonances
CC/NC Coherent pion productions
CC/NC Deep inelastic scattering

\[ \nu + n \rightarrow l + p \]  
\[ \nu + N \rightarrow \nu + N \]  
\[ \nu + N \rightarrow l + N' + \pi \ (\eta, K) \]  
\[ \nu + ^{16}\text{O} \rightarrow l + ^{16}\text{O} + \pi \]  
\[ \nu_{\mu} + N \rightarrow l + N' + \text{hadrons} \]  

($l$: lepton, $N, N'$: nucleon, $m$: integer)

It is possible to investigate various neutrino interactions w/ the K2K near detectors.

(In fact, more precise knowledge of $\nu$-nucleus interaction is vital to improve the accuracy of (future) oscillation measurements)
K2K Near detectors

Scintillating Fiber tracker (SciFi)

- **Main role**
  - To measure: flux, energy spectrum, direction
  - To study: neutrino interaction

- **Detector Types**
  - 1kt Water Cherenkov detector (1kt)
  - Scintillating Fiber Detector (Scifi)
  - Scintillator Bar Detector (SciBar) (2003-)
  - Muon Range Detector (MRD)

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**Scintillating Fiber sheet / Water Sandwich detector**

- 1000t cylindrical water tank w/ 680 20inch PMTs
- Use ring pattern for PID ($\mu / e$)

**Physics output**

- Scintillating Fiber tracker (SciFi)
  - SciScintillating Fiber sheet / Water Sandwich detector

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**Image intensifier**

- Micro-Channel Plate
- CCD camera

**Spectrum shape (>1GeV)**

$M_A$ measurement
SciBar detector

Fine segmented, Full Active Scintillator-Bar Tracker
- Neutrino target is scintillator itself
- 2.5 x 1.3 x 300 cm$^3$ cell (15000 ch)
- (Fairly) large volume
  - (7000 int. / month/10t)
- Tracking Threshold: 8 cm
  - (=0.4 GeV/c Proton)
- Track-finding efficiency
  - >99% (Single Track)
- Excellent $p/\mu(\pi)$ using dE/dx
- misID($\mu \to P$) = 1.7% @ $P_{\text{Eff}}=90$

- High 2-track CC-QE efficiency
- Identify $\nu$ interaction mode clearly

Just constructed in last summer!
CCQE candidate

CCnQE candidate

Area of circle is proportional to ADC.

Hits along the proton track are larger.
NC $\pi^0$ candidate

$\nu_e$ candidate

Large energy deposit in Electron Catcher

NC elastic scattering cand.
Physics output from SciBar

- What can SciBar measure?
  - To estimate SK number of events and $E_\nu$ spectrum (single ring $\mu$-like)
    - $E_\nu$ spectrum at near site from CC-QE ($\nu+n\rightarrow \mu^-+p$)
    - CC-QE form factors
    - CC resonance production form factors
    - $\sigma(n+p\rightarrow \mu^-+p+\pi^+)/\sigma(CC-QE)$ as a function of $E_\nu$
    - $\sigma(n+p\rightarrow \mu^-+p+\pi^0)/\sigma(CC-QE)$ as a function of $E_\nu$
    - $\sigma(n+n\rightarrow \mu^-+n+\pi^+)/\sigma(CC-QE)$ as a function of $E_\nu$
  - CC coherent pion production ($\nu+C\rightarrow \mu^-+C+\pi^+$)
  - CC multi-pion production
  - NC resonance production ($\nu+N\rightarrow \nu+N'+\pi$)
  - $\nu_\mu/\nu_\mu$ flux ratio as a function of $E_\nu$ ($\nu_e$ appearance)
  - nucleon $\Delta s$ measurement
    - $\sigma(n+p\rightarrow n+p)/\sigma(CC-QE)$ as a function of $q^2$
Current activities
Main Motivation is to determine $E_{\nu}$ spectrum shape at near site and $\frac{\sigma_{\text{QE}}}{\sigma_{\text{nonQE}}}$ CCQE vs nonQE.

$\nu_{\mu}$ can reconstruct $E_{\nu}$ through $E_{p,\mu} \sin^2 \theta_{\mu} = c_{\nu \mu} E_{\nu}^{\text{rec}} = \frac{m_{N}E_{\mu} - m_{\mu}^2/2}{m_{N} - E_{\mu} + p_{\mu} \cos \theta_{\mu}}$

charged current analysis
\( \text{Ev spectrum measurement (strategy)} \)

\[
\text{Data}(P_\mu, \theta_\mu) = \sum F(i) \left[ \sigma_{QE} + R_{nQE/QE} \sigma_{nQE} \right]
\]

\( F(i) \) : Flux weight, \( R_{nQE/QE} \) : cross section ratio

SciBar 1trk Data

\( p_\mu \) [GeV/c] vs. \( \theta_\mu \) [degree]
Event sample

Event Sample (CCQE candidates)

1kt : 1-Ring □-like FC events
Scifi, SciBar : MRD matching events
(1Track, 2Track QE, nQE)

CC fraction ~ 98% (SB) 100% (Scifi)
**QE/nQE**

Use proton track direction to enhance CCQE / non QE

<table>
<thead>
<tr>
<th>(1) 1 Track</th>
<th>60%</th>
<th>QE</th>
</tr>
</thead>
<tbody>
<tr>
<td>(2) 2 Track QE enriched</td>
<td>60%(SF) / 70%(SB)</td>
<td>QE</td>
</tr>
<tr>
<td>(3) 2 Track nonQE enriched</td>
<td>85%</td>
<td>nQE</td>
</tr>
</tbody>
</table>

SciBar $\Delta \theta_p$

- **QE**
- **nonQE**

**Expected proton direction assuming CCQE**

**Observed second track**

Expected proton direction

**SciBar**

- **DATA**
  - CC QE
  - CC 1$\pi$
  - CC coherent-$\pi$
  - CC multi-$\pi$
Low $q^2$ correction

K2K observed forward $\mu$ deficit in all ND (KT, SciFi and SciBar).
- A source is non-QE events.
- For CC-1$\pi$,
  - Suppression of $\sim q^2/0.1[GeV^2]$ at $q^2<0.1[GeV^2]$ may exist.
- For CC-coherent $\pi$,
  - The coherent $\pi$ may not exist.

We do not identify which process causes the effect. The MC CC-1$\pi$ (coherent $\pi$) model is corrected to be consistent with data.

Oscillation analysis is insensitive to the choice.

Study of source ongoing with SciBar.
→ next topics
Flux fit result (combine all near detectors)

χ² = 638.1 for 609 d.o.f

- F1 (En < 500) = 0.03 ± 0.02
- F2 (500 ≤ En < 750) = 0.32 ± 0.03
- F3 (750 ≤ En < 1000) = 0.73 ± 0.04
- F4 (1000 ≤ En < 1500) = 1.00

● Φ(Eν) at KEK

7% 3.8%

z nonQE/QE and low energy spectrum are strongly correlated.
Low $q^2$ study in SciBar
Low $q^2$ (forward $\mu$) deficit

Scifi 2track nonQE enriched event

- DATA
  - CC QE
  - CC $1\pi$
  - CC coherent-$\pi$
  - CC multi-$\pi$

(Pure QE sample)

- MiniBooNE
  - From J. Raaf
  - (NOON04)

- Same phenomena is observed by all K2K near detectors in non-QE sample and other exp. in both QE and non-QE sample.
  - It is not due to detector systematics

- This discrepancy cannot be explained by the uncertainty of neutrino spectrum shape.
  - neutrino interaction + nuclear effects

- (As for K2K), source is cc$1\pi$ or coherent $\pi$ or both.
CC1\(\pi\) vs coherent \(\pi\)

**CC 1\(\pi\) (\(\nu+N\rightarrow\mu+N+\pi\))**

**Coherent \(\pi\)**

When pi is absorbed inside nucleus or Proton momentum < 400MeV/c, it looks 2track event. Half of 2nd tracks in 2track-nonQE sample are proton. 2nd track is completely pion. We apply PID to 2nd track and make CC1\(\pi\) enriched/Coherent \(\pi\) samples.
Coherent $\pi$ cross section measurement

SciBar can detect the interaction with high efficiency (20~30%) and purity (~50%) thanks to the fully activity.

This measurement is the first experimental result in a few GeV region for CC int.

→ providing the test of the theoretical model
  ($\sigma(E\nu)$, $\sigma(\text{CC})/\sigma(\text{NC})=2$, $\sigma(A)$ …)

Analysis is very close to final stage.
→ release the result in a few months
NC pi0 measurement in 1kt
Data set


Selection Criteria of $\pi^0$ events
- 25t fiducial volume
- Fully-Contained
- number of rings = 2
- both e-like PID
- $M_{\gamma\gamma}$: 85 ~ 215 MeV/c^2

Non-$\pi^0$ BG very clean $\pi^0$ sample

FC 2ring $\pi^0$: 2496 events
\[ \pi^0 \text{ momentum (FC 2ring } \pi^0 \text{ sample)} \]

(MC is normalized by area)

\[ N_{NC1\pi^0} = N_{FC2\pi^0}^{obs} \times r_{\text{pure}} \times \text{corrfid} \]

\[ \text{eff} \]

large NC fraction
\[ \sim 87\% \]

\[ \frac{\sigma(\text{NC1}\pi^0)}{\sigma(\nu_\mu \text{CC})} = 0.065 \pm 0.001 \pm 0.007 \]

at the K2K beam energy, \( <E_\nu> \sim 1.3 \text{ GeV} \)

cf. \[ \frac{\sigma(\text{NC1}\pi^0)}{\sigma(\nu_\mu \text{CC})} = 0.064 \] from NEUT

Hep-ex/0408134
Submitted to PLB
On-going analysis
On going analysis

SciFi-MA study (first measurement for water) is almost done. → results appear soon.
SciBar-MA analysis is just started.

NC/CC ~20% → NC/CC 10~20 %

Energy dependent cross section (ratio to CCQE)

ν̄e measurement (SciBar, 1Kt) related with K2K analysis.
The recent discovery of neutrino oscillation has renewed interest in the $\nu$-nucleus scattering in the sub to a few GeV region.

In the K2K near detectors, the following topics are studied.
- CC coherent pion production (appear soon)
- NC pi0 production (submitted in PLB)
- $M_A$ measurement for water target (appear soon)

On-going analysis
- $\Delta (\text{CC1p})/\Delta (\text{CC})$, $\Delta (\text{NC elastic})/\Delta (\text{QE elastic})$
- $M_A$ (carbon) …..

Many physics results will be released around this summer. Stay tuned!
Supplement
NEUT: K2K Neutrino interaction MC

- **CC quasi elastic (CCQE)**
  - Smith and Moniz with $M_A=1.1\text{GeV}$
- **CC (resonance) single $\pi\text{(CC-1}\pi\text{)}$**
  - Rein and Sehgal’s with $M_A=1.1\text{GeV}$
- **DIS**
  - GRV94 + JETSET with Bodek and Yang correction.
- **CC coherent $\pi$**
  - Rein&Sehgal with the cross section rescale by J. Marteau
- **NC**
  + Nuclear Effects

(Nucl.Phys.Proc.112,p171)