Status of the T2K experiment

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1. Introduction
2. T2K experiment
   - Features and Prospects
   - Hadron-production measurement
3. Short summary of the construction status
4. Summary
Precise measurement of $E_{\nu}$

\[ P(\nu_\alpha \rightarrow \nu_\beta) = \sin^2(2\theta) \sin^2 \left( \frac{1.27 \Delta m^2 L}{E_\nu} \right) \]

\[ U_{\alpha i} = \begin{pmatrix} \cos \theta & \sin \theta \\ -\sin \theta & \cos \theta \end{pmatrix} \]

Neutrino oscillation

- neutrino flavor mixing

(Simplified two-flavor case)

$\Delta m^2 = m_1^2 - m_2^2$ in eV$^2$

traveling distance in km

neutrino’s energy in GeV

- Reduction of $\nu_\alpha$
- Distortion of $E_{\nu \alpha}$ spectrum
- Appearance of $\nu_\beta$

Observed by several experiments

Neutrino has mass and its flavor is mixing
Three flavor mixing

\[
U = \begin{pmatrix}
1 & 0 & 0 \\
0 & c_{23} & s_{23} \\
0 & -s_{23} & c_{23}
\end{pmatrix}
\begin{pmatrix}
c_{13} & 0 & s_{13}e^{-i\delta} \\
0 & 1 & 0 \\
-s_{13}e^{i\delta} & 0 & c_{13}
\end{pmatrix}
\begin{pmatrix}
c_{12} & s_{12} & 0 \\
-s_{12} & c_{12} & 0 \\
0 & 0 & 1
\end{pmatrix}
\text{diag}(1, e^{i\alpha}, e^{i\beta})
\]

\[\Delta m_{12}^2 + \Delta m_{23}^2 + \Delta m_{31}^2 = 0\]

- **Present knowledge**

  \[\Delta m_{\text{solar}}^2 = 8 \times 10^{-5} \text{ eV}^2\]  
  \[\sin^2(2\theta_{12}) = 0.86\]  
  \[\Delta m_{\text{atm}}^2 = (2.2\sim3.0) \times 10^{-3} \text{ eV}^2\]  
  \[\sin^2(2\theta_{23}) > 0.92\]  

  \[\sin^2(2\theta_{13}) < 0.15\]  
  \[\text{at } \Delta m^2 = 2.5 \times 10^{-3} \text{ eV}^2\]  

  \(\delta : \text{unknown}\)

  \(\text{sign}(\Delta m_{\text{atm}}^2) : \text{unknown}\)
What does T2K aim for?

1. discovery of a finite $\theta_{13}$
   • open the possibility to measure CPV phase $\delta$
   • important interplay with mass ordering and $0\nu\beta\beta$

\[ |m_{ee}| \equiv \left| \sum_i m_i U_{ei}^2 \right| \]

**effective mass**

2. precise measurement of other parameters
   • Is $\theta_{23}$ maximal mixing?

3. CPV in lepton sector
   hint on Baryon# asymmetry of Universe

\[ U_{e3} = s_{13} e^{-i\delta} \]

\[
\begin{pmatrix}
0.8 & 0.5 & \square \\
0.4 & 0.6 & 0.7 \\
0.4 & 0.6 & 0.7
\end{pmatrix}
\]
T2K experiment (J-PARC E11)
~T2K: Tokai to Kamioka LBL Neutrino Oscillation Experiment~

- T2K 1st-phase
  - \textit{discovery of a finite }\theta_{13}\textit{ by observing }\nu_e\textit{ appearance}
  - measure }\nu_e\textit{ app. in T2K-1 }\rightarrow\delta\textit{ (CPV) in T2K 2nd-phase}
  - \textit{precise measurement of }\theta_{23}, \Delta m^2_{23}\textit{ by }\nu_\mu\textit{ disappearance}

\textit{Experiment : 2009 ~}
**Overview of T2K experiment**

- **observable** = \( \Phi(E_\nu) \times \sigma(E_\nu) \)
  - CC interaction
  - FNAL SciBoone exp.

- **To extrapolate** \( \Phi_{SK} \) is a key issue
  - \( \Phi_{SK}(E_\nu) \neq \Phi_{ND}(E_\nu) \) even w/o oscillation due to effect of non-point like source

\[
\Phi_{SK\,\text{exp.}}(E_\nu) = R_{F/N}(E_\nu) \times \Phi_{ND}(E_\nu)
\]

Hadron production measurement
Narrow-band intense neutrino beam

- Off-axis beam method (ref. BNL-E889 proposal)

\[ L = 295 \text{ km} \]
\[ \Delta m^2_{23} = (2.2 \sim 3.0) \times 10^{-3} \text{ eV}^2 \]

Oscillation max.
\[ E_V = 0.5 \sim 0.7 \text{ GeV} \]

- \( \times 2 \sim 3 \) intense than OA 0°
- \(~2200 \nu_\mu\) int. in total (~1600 \(\nu_\mu\) CC int.) for 1yr * 22.5kt(SK)
- Small high energy \(\nu\) tail \(\rightarrow\) reduce bkg. to \(CCQE\)
- \(\nu_e \sim 0.4\%\) at \(\nu_\mu\) peak

\[ \frac{\text{E}_\nu}{\text{GeV}} \]

\[ \frac{\text{P}_{\pi}}{\text{GeV/c}} \]
ν Energy Reconstruction

- Energy Rec. is possible for **CC Quasi-Elastic (CCQE)**

\[
E_{\nu}^{\text{rec}} = \frac{m_N E_{\mu} - m_\mu^2 / 2}{m_N - E_{\mu} + p_\mu \cos \theta_\mu}
\]

**CCQE**: \( \nu_{\mu(e)} + n \rightarrow \mu(e) + p \)

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**Diagram**

- T2K's beam energy
- Eν (GeV)
- ν Cross-sections
- Total (CC+NC)
- Total (CC)
- CC Quasi-elastic
- CC DIS
- CC 1π
- NC 1π

**Graph**

- # of events
- CCQE events
- non-QE events
- Ev_{\text{rec}} - Ev_{\text{true}} (GeV)
- 1Rμ
- 100
- 200
- 300
- 400
- 0
- -0.5
- 0
- 0.5
- 1
Super Kamiokande (far detector)

- 50 kton water Cherenkov detector (fiducial volume: 22.5 kton)
- ~10000 x 20 inch PMTs (inner detector)
- good hit-ID: e-like(shower ring) / μ-like
- $\delta E_{\text{scale}} \sim 2\%$

**SK has been fully reconstructed**

Data taking of SK-III since July/2006
Physics prospects

1. $\theta_{13}$ measurement by $\nu_e$ appearance
2. Precise measurement of $(\theta_{23}, \Delta m^2_{23})$
3. Hadron-production measurement
$\theta_{13}$ measurement by $\nu_e$ appearance

- simplified probability of $\nu_\mu \to \nu_e$ \[ \Delta m^2_{31} = \Delta m^2_{32} \gg \Delta m^2_{12} \]

\[ P(\nu_\mu \to \nu_e) \approx \sin^2(2\theta_{13}) \sin^2 \theta_{23} \sin \left[ 1.27 \Delta m^2_{31} L/E \right] \]

common as $\nu_\mu$ disappearance

- However, more exact $P(\nu_\mu \to \nu_e)$ composes not only $\theta_{13}$ but also other unknown parameters

\[ P(\nu_\mu \to \nu_e) = 4C_{13}^2 S_{13}^2 S_{23}^2 \sin^2 \phi_{31} - 8C_{13}^2 C_{12}C_{23}S_{12}S_{13}S_{23} \sin \delta \sin \phi_{32} \sin \phi_{31} \sin \phi_{21} + \ldots \]

T2K observable: $P(\nu_\mu \to \nu_e) \to \sin^2(2\theta_{13})$

some ambiguities due to unknown parameters, but more sensitive than the current limit

and, it is possible to measure CPV by \[
\frac{P(\nu_\mu \to \nu_e) - P(\nu_\mu \to \bar{\nu}_e)}{P(\nu_\mu \to \nu_e) + P(\nu_\mu \to \bar{\nu}_e)} \]
in T2K-II
• $\nu_e$ appearance
• signal : $e^-$ from $\nu_e$ CCQE
• background
  • beam intrinsic $\nu_e$
  • $\nu_\mu$ NC1$\pi^0$, in which $\pi^0$ is mis-ID as $e^-$

expected signal + bkg
sin²(2 $\theta_{13}$) = 0.1
$\Delta m^2 = 2.5 \times 10^{-3}$

# of events in 0.35<$E_\nu$(GeV)<0.65
- signal 103
- Beam $\nu_e$ bkg. 13
- $\nu_\mu$ bkg (CC+NC1$\pi^0$) 10

understanding bkg. is a key issue
Expected sensitivity of $\theta_{13}$

- > x10 improvement from CHOOZ results for almost any $\delta$
  
  $\sin^2(2\theta_{13}) = 0.008$ (90% C.L.) for $\delta=0$, $\Delta m^2_{13}=2.5\times10^{-3}$ eV$^2$, $\sin^22\theta_{23}=1$

90% C.L. sensitivity @5 years ($5 \times 10^{21}$ pot) w/ stat. + 10% bkg. systematic error
Complementary measurement of $\theta_{13}$

- Reactor Experiment (DoubleChooz, DayaBay, RENO ...)
- $\nu_e$ disappearance $\rightarrow$ pure $\sin^2 2\theta_{13}$ measurement

\[
P(\nu_e \rightarrow \nu_e) = 1 - \sin^2 \theta_{13} \cdot \sin^2 (1.27 \Delta m^2_{31} L/E) + O(\Delta m^2_{21}/\Delta m^2_{31})
\]

- not sensitive to CPV phase $\delta$

Comparison both results

- $\delta$, $\text{sign}(\Delta m^2_{31})$, $\sin \theta_{23}$
- T2K measurement
- Reactor measurement

from F.Suekane-san’s slide (JPS2007,Mar)
precise measurement of \((\theta_{23}, \Delta m^2_{23})\)

- \(v_\mu\) disappearance
- goal
  - \(\delta(\sin^22\theta_{23}) \sim 0.01\)
  - \(\delta(\Delta m^2_{23}) \sim < 1 \times 10^{-4} \text{ eV}^2\)

Requirements on systematic error

- Non-QE/QE ratio : <5%
- Energy scale : <2%
- **flux normalization : <10%**
- Spectrum shape : <20%
- Spectrum width : <10%

required errors on \(\Phi_{SK}^{\text{exp.}}(E_v)\)

\[
(sin^2 2\theta, \Delta m^2) = (1.0, 2.7 \times 10^{-3} \text{ eV}^2)
\]

5 years (5 x 10^{21} pot)

Stat. only (OA2.5°)

---68%CL

---90%CL

---99%CL

\((-15\text{MeV/22.5kt/5yr}) \times 10^{-1}\)
Hadron-production measurement

- expect $\Phi_{SK_{exp}}(E_\nu)$ precisely in order to reduce syst. errors
- $\Phi_{SK_{exp}}(E_\nu) = R_{F/N}(E_\nu) \times \Phi^{ND}(E_\nu)$
- $R_{F/N}(E_\nu)$ is sensitive to hadron-production distribution
- Requirements on the accuracy of $R_{F/N}(E_\nu)$
  - $\nu_e$ app.: $\delta(N_{bkg}) < 10\%$ → $\delta R_{F/N}(E_\nu) < 2\sim3\%$
    Ev: 0-1GeV and 1-10GeV
  - $\nu_\mu$ disapp.: required errors on $\Phi_{SK_{exp}}$ → $\delta R_{F/N}(E_\nu) < 2\sim3\%$
    Ev: 0-1.5GeV,100MeV/bin
- There are no measurements of 30GeV ~ 50GeV p+C

*Experimental measurement of the hadron-production is necessary!!*
• Requirements on hadron-production measurements

• Measure \((P_{\pi}, \theta_{\pi})\) distribution with <10% stat. error for each 150MeV/c x 20mrad bin in the region: \(0.3 < P_{\pi}(\text{GeV/c}) < 10\) and \(0 < \theta_{\pi}(\text{mrad}) < 400\)

\[ \delta R_{F/N}(E_{\nu}) < 2\sim3\% \]
Ev: 0-1.5GeV, 100MeV/bin

• Measure K/\pi ratio with <10% accuracy

• high energy \(\nu_\mu \rightarrow \text{NC}1\pi^0\) bkg. from K decay

\[ \delta R_{F/N}(E_{\nu}) < 2\sim3\% \]
Ev: 0-1GeV and 1-10GeV
CERN NA61 Experiment

- Detector w/ Large acceptance
  - TPC w/ magnetic field + TOF
  - PID(p,K,π ..) w/ dE/dx and TOF
- p+C for T2K in 2007 (,2008)
  - thin(1cm), thick(10cm,90cm) targets
  - beam time in 2007 fall (29days) ← devoted for T2K purpose
- Impact of NA61

<table>
<thead>
<tr>
<th></th>
<th>T2K goal</th>
<th>Error from R_{F/N} w/ NA61</th>
</tr>
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<tbody>
<tr>
<td>$\delta N_{bkg}$ for ve app.</td>
<td>10%</td>
<td>&lt; 4%</td>
</tr>
<tr>
<td>$\delta (\sin^2 2\theta_{23})$</td>
<td>1%</td>
<td>0.5%</td>
</tr>
<tr>
<td>$\delta (\Delta m^2_{23}) \times 10^{-4}$ eV$^2$</td>
<td>&lt; 1</td>
<td>0.15</td>
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→ get ready for T2K which starts in 2009
Construction status
J-PARC
(Japan Proton Accelerator Research Complex)

Construction: 2001 ~ 2008

3GeV Synchrotron (25Hz, 1MW)

Material/Life Science Facility

50GeV Synchrotron (0.75 MW)

Hadron Experimental Facility

Linac (350m)

Neutrino Facility

Joint Project between KEK and JAEA
• Construction & Commissioning are in progress

• Linac successfully accelerated up to the design energy of 181MeV

• MR commissioning will start in 2008
Neutrino Facility at J-PARC

Beam-line construction
First Beam in 2009.Apr

Primary Beamline

Primary Proton

Target/Horn (Target Station)

Beam Dump

Decay volume
110m ($\pi \rightarrow \mu\nu$)

Near Neutrino Detector

to Super-Kamiokande
Beam direction

- Requirement on the beam direction < 1 mrad
- reduce syst. error of $\Delta m^2_{23}$ caused by $\delta E_{\nu}$
- $\delta (p$ beam pos. on target) < 1 mm
- beam-line alignment using GPS
- monitor direction of the $\mu$ and $\nu_\mu$

1 month data w/ 1% beam
(red: $p$ beam hits the center of tgt, blue: off-center of tgt by 3mm)

- $\nu_\mu$ beam monitor @ 280m
  - on-axis of $\nu_\mu$ beam
  - 10m x 10m
  - Fe/Scintillator sandwich x 16

- muon monitor @ ~110m
  - IC & semi-conductor array
  - 150 cm x 150cm
  - spill by spill monitor

$\nu_\mu$ beam monitor @ 280m
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A New Neutrino Beam line with MW fast ext. beam

• Technical challenges
  • Thermal shock $\rightarrow$ use graphite for target and beam dump
  • Heat load $\rightarrow$ water cooling everywhere
  • Radiation $\rightarrow$ shield & remote maintenance

• Construction & final R&D of each component are in progress
Near Detectors @ 280m

- Off-axis detector
  - measure $\nu$ beam energy, flux and flavor contents
  - study $\nu$ cross section (water/carbon)
  - Tracker(FGD,TPC), Pi0 detector and EM calorimeter in the UA1 magnet (0.2T)

- On-axis detector
  - $\nu$ beam direction monitor
  - Beam/detector commissioning will start with on-axis detector in Apr/2009
  - commissioning of off-axis detector in the fall of 2009
Summary

• T2K
  • off-axis beam → $E_\nu \sim$ sub-GeV & SK as far detector
  • discover a finite $\theta_{13}$ >x10 improvement
    • if we measure $\nu_e$ app. in T2K-I → CPV in T2K-II
    • complementary with Reactor experiment
    • interplay with mass ordering and $0\nu\beta\beta$
  • precise measurement: $\delta(\sin^2\theta_{23})\sim1\%$, $\Delta m^2_{23}<1 \times 10^{-4}$ eV$^2$
  • new hadron-production measurement: CERN NA61

• Construction of Accelerators and Neutrino Facility at J-PARC
  are in progress

Start from Apr/2009