Tokai 2 Kamioka
Status and Prospects

Antonin Vacheret
for the T2K Collaboration
Tuesday 7th September
NOW 2010, Otranto, Lecce, Italy
Overview

- T2K physics goals
- Experimental sensitivity
- Overview of the experiment
- Status and prospects
Neutrino oscillation matrix

Neutrino oscillation described by unitary matrix $U_{\text{MNSP}}$

$$U_{\text{MNSP}} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

$c_{ij} = \cos \theta_{ij}, s_{ij} = \sin \theta_{ij}$

3 mixing angles ($\theta_{12}, \theta_{23}, \theta_{13}$)

1 CP violation phase ($\delta$)

2 mass$^2$ differences ($\Delta m^2_{ij} = m_i^2 - m_j^2$)

- value of $\theta_{13}$ is only constrained by data
- $\delta$ is unknown
- sign of $\Delta m^2_{\text{atm}}$ is not yet known

Necessary to complete oscillation picture!
T2K Goals

- measure last unknown mixing angle $\theta_{13}$ using $\nu_\mu \rightarrow \nu_e$ appearance
  potentially open up $\delta_{CP}$ search in neutrino sector

- measure precisely the atmospheric parameters using $\nu_\mu \rightarrow \nu_\mu$ disappearance
  is there a symmetry between 2nd and 3rd generation?
$\nu_\mu \rightarrow \nu_e$ appearance

$$P(\nu_\mu \rightarrow \nu_e) \approx \sin^2 2\theta_{13} \sin^2 \theta_{23} \sin^2 (\Delta m_{13}^2 \frac{L}{4E_\nu})$$

Sensitivity down to $0.006$ @ $\Delta m_{23}^2 = 2.5 \times 10^{-3}$ eV$^2$
$\nu_\mu$ disappearance

\[ P(\nu_\mu \rightarrow \nu_\mu) \approx 1 - \sin^2 2\theta_{23} \sin^2\left(\frac{\Delta m^2_{23} L}{4E_\nu}\right) \]

Enter precise measurement era

- $\delta(\sin^2 2\Theta_{23}) \sim 0.01$
- $\delta(\Delta m^2_{13}) \sim 1 \times 10^{-4} \text{ eV}^2$

K2K collaboration Phys. Rev. D. 74 072003

T2K @ 90%CL

From MINOS presentation at Neutrino 2010
† Super-K collaboration preliminary result
The T2K baseline

J-PARC Intense proton beam: 750 KW at design value

Far detector Super-Kamiokande: 50 kT Water Cherenkov detector
- high statistics CCQE event reconstructed with high efficiency & purity

Unique baseline: first Off-axis neutrino beam (angle @ 2.5°)
- Narrow band beam ideal for $\nu_e$ search
- Peak energy at oscillation maximum < 1 GeV: Quasi-elastic (CCQE) processes dominate
- Low contamination from other $\nu$ flavour (0.5% $\nu_e$)
- Background from misreconstructed high energy neutrinos significantly reduced

Near detectors @ 280 m
- Measure on axis and off-axis beam

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Analysis strategy

Number of reconstructed events ($\nu_\mu$ and $\nu_e$) at SK can be predicted using

- near detectors (off-axis beam, neutrino cross sections)
- hadron production measurements (NA-61)

Compare prediction with SK observation to extract oscillation parameters:

$$N(E_{\nu}^{rec}) = \Phi_{SK}^{exp}(E_{\nu}^{true}) \times \sigma(E_{\nu}^{true}) \times P_{osc}(E_{\nu}^{true}) \times \epsilon_{SK}(E_{\nu}^{true}) \times f(E_{\nu}^{rec}, E_{\nu}^{true})$$

**beam flux** **Cross section** **Osc. Prob.** **Det eff.** **SK Det response**

omit integral on $E_{\nu}^{true}$

Flux at Near Det:

$$\Phi_{ND} = \frac{N_{ND}^{obs}}{(\sigma_{ND} \times \epsilon_{ND})}$$

Far to Near extrapolation factor

Flux at SK:

$$\Phi_{SK} = R_{SK/ND} \times \Phi_{ND}$$

- Hadron production measurement
- Cross section measurements (SciBooNE, T2K ND)
- Normalisation & $E_{\nu}$ spectrum from T2K ND

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## The T2K Collaboration

<table>
<thead>
<tr>
<th>Country</th>
<th>Institutions</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>France</strong></td>
<td>CEA Saclay, IPN Lyon, LLR E. Poly., LPNHE Paris</td>
</tr>
<tr>
<td><strong>Germany</strong></td>
<td>U. Aachen</td>
</tr>
<tr>
<td><strong>Japan</strong></td>
<td>ICRR Kamioka, ICRR RCCN, KEK, Kobe U., Kyoto U., Miyagi U. Edu., Osaka City U., U. Tokyo</td>
</tr>
<tr>
<td><strong>Spain</strong></td>
<td>IFIC, Valencia, U. A. Barcelona</td>
</tr>
<tr>
<td><strong>STFC/RAL</strong></td>
<td>STFC/Daresbury</td>
</tr>
<tr>
<td><strong>Switzerland</strong></td>
<td>U. Bern, U. Geneva, ETH Zurich</td>
</tr>
<tr>
<td><strong>Russia</strong></td>
<td>KEK, Kobe U., Kyoto U., Miyagi U. Edu., Osaka City U., U. Tokyo</td>
</tr>
<tr>
<td><strong>United Kingdom</strong></td>
<td>Imperial C. London, Queen Mary U. L., Lancaster U., Liverpool U., Oxford U., Sheffield U., Warwick U.</td>
</tr>
</tbody>
</table>

~500 members, 61 Institutes, 12 countries
The J-PARC facility

- North
- Construction
- JFY2001~2008
- 181 (400) MeV Linac
- Neutrino Beam
- 30 GeV Main ring
- 750 kW (design value)
- 2007
- 2008
- 2009

Bird’s eye photo in January of 2008

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The neutrino beam line

Fast extracted beam from MR ring
- 6 bunches/spill (increased to 8 in Fall 2010)
- Superconducting combined function magnets for proton transport

Primary beam monitors
- Intensity(CT), position(ESM), profile(SSEM), beam loss(IC), beam profile at target(OTR)

Target Station
- graphite core target (26 mm(D) x 900 mm L)
- 3 horns @ 250 kA (320 kA)

Target station connected to decay pipe 110 m long filled with Helium

Beam dump
- Hadron absorber graphite modules

Secondary beam monitors
- muon profile after beam dump: ionisation chambers and SiPIN (MUMON)
- Emulsion exposures (low intensity)

Neutrino detectors at 280 m
Super-K direction given by GPS
INGRID On-axis monitor

On-Axis detector is crucial for off-axis measurements:

- monitor beam direction, intensity and mean energy
- beam coverage $\sim 10 \times 10 \, \text{m}^2$
- Off-axis angle measurement accuracy goal is $1 \, \text{mrad}$ ($< 15 \, \text{MeV}$ on off-axis peak energy)
- beam position resolution $\sim 7\,\text{cm}$ corresponding to $\sim 3\,\text{mm}$ shift at proton target
- $\sim 10 \, k \, \nu$ interactions per day at full power

2 remaining diagonal modules and 1 full plastic “proton” module to be installed for next T2K run

INGRID “cross” is formed with 14 identical modules + 2 diagonal modules made of plastic scintillator planes and 6.5 cm thick Iron planes surrounded by veto planes
The Off-axis near detector (ND280) provides

- Off axis beam measurement based on CCQE
- Beam nue contamination
- Super-K background measurements (NCπ₀)

Two target regions:

- The P0D (Brass/Plastic segmented) : π₀ detector
- The tracker region : Fined grained plastic detector and TPC
- Both region have passive water planes

Large Calorimeter coverage (Plastic/Pb segmented)

- Additional NCπ₀ production measurement in tracker and PID, hermicity, active veto

Side Muon ranging detector

- Neutrino Rate, Side muons, cosmics trigger

Precise cross-section measurements with very large statistics !!!
Near Detector Technologies

- Scintillator + WLS fibre read out by novel MPPC ND280
  - Low cost high performance and uniformity detector element
  - novel solid state photosensor insensitive to magnetic field

- HAMAMATSU MPPC 667 Pixels array
  - Photon counting, high PDE, low power consumption, ceramic package
  - ~ 56 800 channels
  - T2K first experiment to use MPPC at such a large scale

- Very Large TPC based on MicroMegas read out
  - 3x large modules with double wall structure
  - Sensitive volume 180 x 200 x 70 cm
  - Precise assembly, commissioning and alignment within mm
  - 124 000 channels

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The Far detector : Super Kamiokande IV

50 (22.5 Fid.) kT Water Cherekov detector with 11 129 20” PMTS in inner detector (ID) and 1885 8” PMTS instrumenting outer detector (OD)

Super-K in operation since 1996

- Dead-timeless read out electronics and DAQ upgrade in 2008
- GPS system used to select time arrival of beam events

Water transparency (light att. length)

90 m

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T2K Status
Beam performance

First T2K run completed (January to June 2010)

- $3.3 \times 10^{19}$ protons accumulated for T2K analysis
- 50 kW stable operation with trials at 100 kW
- Super-K live fraction in excess of 99%
Beam Monitors

Proton beam precisely tuned (less than 1 mm deviation at target) to minimise beam loss and control secondary beam spill by spill.

MUMON: profile center < +/- 1 mrad ($\Delta E_v^{\text{peak}} \approx 2\%/$mrad)
Beam stability @ target

**Extrapolated Position**
- Target $\varnothing 26$ mm

**Extrapolated Angle**

**Extrapolated width**
- Target radius 13 mm

**Accumulated beam profile @ target (Jan-June period)**
- Target $\phi=26$ mm
- $\mu = 0.27$ mm, $\sigma = 4.13$ mm
- $\mu = 0.85$ mm, $\sigma = 4.19$ mm
Neutrino beam depends upon secondary beam geometry and hadron distribution off target

NA-61/SHINE: dedicated hadron production experiment using T2K target to reduce uncertainties in hadron production models

- Pilot run in 2007 and high statistics run in 2009: p(30 GeV) with Carbon thin target and T2K replica target
- Preliminary results from 2007 used in T2K beam MC
INGRID measurements

- First event
- Beam Profile X
- Beam Profile Y
- Beam Profile Center X
- Beam Profile Center Y

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Interaction vertex reconstruction

- off-axis beam profile clearly visible in both target regions (FGD and P0D)

Particle identification (TPC dEdx)

- crucial for measuring $\nu_\mu$ and beam $\nu_e$ spectra
ND280 timing & rate stability

**P0D reconstructed vertices**

Integrated 3D Vertices

FGD activity in time with beam

Events / $10^{15}$ POT

Average rate = 0.306 events / $10^{15}$ POT
Chi-square/ndf = 28.36/20

Daily DsECal cluster rates

DsECal cluster times; Runs 31 & 32

In beam time
Out of beam time

Time relative to trigger ($\mu$s)

Protons @ CT5
DsECal clusters

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ND280 off-axis neutrino events
Super-K time distribution

\[ \Delta T_0 = \text{SK trig time} - \text{T2K beam trigger time} \]

- Very good synchronisation with T2K beam achieved

RMS \approx 26 \text{ ns}
Super-K $\nu$ events

single $\mu$-like ring event

$P_\mu = 1025$ MeV/c  
1 decay-$e$

$P_\mu = 1438$ MeV/c  
2 decay-$e$

$\mu$-like multi-rings event
### T2K neutrino events at Super-K

<table>
<thead>
<tr>
<th>Category</th>
<th>Number</th>
</tr>
</thead>
<tbody>
<tr>
<td>total POT</td>
<td>(3.23 \times 10^{19})</td>
</tr>
<tr>
<td>Fully Contained (FC)</td>
<td>33</td>
</tr>
<tr>
<td>Fiducial volume cut + visible energy &gt; 30 MeV (FCFV)</td>
<td>23</td>
</tr>
</tbody>
</table>

**Points:** Event vertex  
**Arrow:** 1st-ring direction (projection of 2m length arrow)

![Vertex X vs Y](image1.png)  
![Vertex R vs Z](image2.png)

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Super-K Outer detector results

ΔT0 Distribution, After ODT Cuts, Stacked

ODC: OD contained
ODEX: OD exiting
ODEN: OD entering from ID

Accumulated Events, After ODT Cut

KS Test vs. Straight Line
Max Dist: 0.159
Prob.: 0.528
Slope 0.77

Time Between Events, After ODT Cut

Fitted Rate: 0.80 +/- 0.3022

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Summary

Jan-Jun 2010 T2K run completed

- Continuous beam operation at ~ 50 kW
- Good overall stability of beam and detector performance
- Accumulated $3.23 \times 10^{19}$ PoT
- Measured 23 neutrino beam events (FCFV) at Super-K
- Analyses are ongoing at near and far detectors

Summer-fall Shut down

- Calorimeter modules installation and commissioning: full coverage at ND280
- New kicker magnet & power supplies installed
- INGRID modules assembly and installation

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Prospects for next year

Next T2K run scheduled this fall

- Expected beam at 150 kW x $10^7$ s until July 2011
- High statistics at near detectors
- Sensitivity to $\sin^22\theta_{13} \sim 0.05$

\[ \text{90\% CL } \theta_{13} \text{ Sensitivity} \]

Systematic Error Fraction
- 5\% sys error
- 10\% sys error
- 20\% sys error
Normal Hierarchy

\[ \sin^22\theta_{13}, \text{ Sensitivity} \]

Protons on Target

July 2011
3.75 MW x $10^7$ s
The End

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Beam power

$\text{PMR (8-bunch@30GeV) = 1.6 \times \text{PRCS / MRCYCLE}}$

( ): Beam transfer ratio from RSC to MR

RCS POWER FOR MR $\star 0.72\text{MW}$

MR POWER AT 30GeV

- 3.2 sec (5.0%)
- 3.52 sec (4.5%)
- 6 sec (2.7%)

2.47 sec (6.5%)

2.23 sec (7.2%)

(maximum cycle with existing power supply)

1.0 sec (16%)

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### Super Kamiokande event selection

J-PARC neutrino events selected using GPS time

SK selection and cuts values are fixed for T2K

- **Unbiased selection**

<table>
<thead>
<tr>
<th><strong>For $\nu_\mu$ disappearance</strong></th>
<th><strong>For $\nu_e$ appearance search</strong></th>
</tr>
</thead>
<tbody>
<tr>
<td>Timing coincidence w/ beam timing (+TOF)</td>
<td></td>
</tr>
<tr>
<td>Fully contained (No OD activity)</td>
<td></td>
</tr>
<tr>
<td>Vertex in fiducial volume (Vertex &gt;2m from wall)</td>
<td></td>
</tr>
<tr>
<td>Evis &gt; 30MeV</td>
<td>Evis &gt; 100MeV</td>
</tr>
<tr>
<td># of ring =1</td>
<td></td>
</tr>
<tr>
<td>$\mu$-like ring</td>
<td>e-like ring</td>
</tr>
<tr>
<td>No decay electron</td>
<td></td>
</tr>
<tr>
<td>Inv. mass w/ forced-found 2\textsuperscript{nd}</td>
<td></td>
</tr>
<tr>
<td>$E_\nu^{\text{rec}}$ &lt; 1250MeV</td>
<td></td>
</tr>
</tbody>
</table>
Precision measurement of $\theta_{23}$, $\Delta m_{23}^2$
possible systematic errors and phase-1 stat.

• Systematic errors
  • normalization (10% $\rightarrow$ 5% (K2K))
  • non-qe/qe ratio (20% (to be measured))
  • E scale (4% (K2K 2%))
  • Spectrum shape (Fluka/MARS $\rightarrow$ (Near D.))
  • Spectrum width (10%)

Goal

$\delta(\sin^2 2\theta_{23}) \sim 0.01$
$\delta(\Delta m^2_{23}) < 1 \times 10^{-4}$ eV$^2$
T2K sensitivity and discovery potential

$\sin^2 2\theta_{13}$ vs. Integrated beam power (MWx10^7 s)

Solid: 3σ discovery
Dashed: 90% CL sensitivity

$\sin^2 2\theta_{12} = 0.87$
$\sin^2 2\theta_{23} = 1.0$
$\Delta m_{32}^2 = 7.6 \times 10^{-5} \text{eV}^2$
$\Delta m_{33}^2 = 2.4 \times 10^{-3} \text{eV}^2$
$\delta = 0$

3.75 MWx10^7 s (Proposal)
100 kWx10^7 s
$\theta_{13}$ sensitivity with varying $\delta_{CP}$ \text{ NH}
$\theta_{13}$ sensitivity with varying $\delta_{CP}$ IH