Status of the T2K Experiment

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● Three neutrino flavor mixing
● The T2K Experiment
  – SK
  – On-axis detectors
  – Off-axis detectors (ND280)
● Summary
Two Flavor Oscillation

- Conversion probability in vacuum

\[ P(\nu_\beta | \nu_\alpha) = \langle \nu_\beta(t) | \nu_\alpha(0) \rangle^2 = \sin^2 2\theta \sin^2 \left( \frac{c^3 \Delta m^2 L}{\hbar 4E} \right) \]

→ No mixing for massless \( \nu \)'s

→ \( L/E \) must be large for small mass differences

### Atmospheric neutrinos:

\[ \approx (\nu_\mu \rightarrow \nu_\tau) \]

\[ \Delta m^2_{\text{atm}} = 1.5 - 3.5 \cdot 10^{-3} \text{ eV}^2 \]

\[ 36.8^\circ < \theta_{\text{atm}} < 45^\circ \]

### Solar neutrinos:

\[ \approx (\nu_e \rightarrow \nu_\mu) \]

\[ \Delta m^2_{\text{solar}} = 8.0^{+0.6}_{-0.4} \cdot 10^{-5} \text{ eV}^2 \]

\[ \theta_{\text{solar}} = \left( 33.9^{+2.4}_{-2.2} \right)^\circ \]
Three Neutrino Flavor Oscillation

\[
\begin{pmatrix}
\nu_e \\
\nu_\mu \\
\nu_\tau
\end{pmatrix} =
\begin{pmatrix}
1 & 0 & 0 \\
0 & c_{23} & s_{23} \\
0 & -s_{23} & c_{23}
\end{pmatrix}
\begin{pmatrix}
c_{13} & 0 & e^{i\delta}s_{13} \\
0 & 1 & 0 \\
-e^{-i\delta}s_{13} & 0 & c_{13}
\end{pmatrix}
\begin{pmatrix}
c_{12} & s_{12} & 0 \\
-s_{12} & c_{12} & 0 \\
0 & 0 & 1
\end{pmatrix}
\begin{pmatrix}
\nu_1 \\
\nu_2 \\
\nu_3
\end{pmatrix}
\]

Atmospheric neutrinos: \(\theta_{23} \approx 45^\circ\)

Reactor + accelerator \(\nu's\): \(\theta_{13} < 9^\circ\)

Solar neutrinos: \(\theta_{12} \approx 34^\circ\)

Conversion probability:

\[
P(\nu_\alpha \to \nu_\beta) = \delta_{\alpha\beta} - 4 \sum_{i > j} R(U_{\alpha i}^* U_{\beta i} U_{\alpha j} U_{\beta j}^*) \sin^2 \left(1.27 \Delta m_{ij}^2 \frac{L}{E}\right) + 2 \sum_{i > j} I(U_{\alpha i}^* U_{\beta i} U_{\alpha j} U_{\beta j}^*) \sin \left(2.54 \Delta m_{ij}^2 \frac{L}{E}\right)
\]

Described by two \(\Delta m^2\), three \(\theta's\) and one CP phase (\(\delta\))
... Three Neutrino Oscillations

- $\theta_{13} < 9$ degrees

- CP violation
  - Small in quark sector
  - $\theta_{13}$ must be $> 0$
  - Experimental signature:
    $$ P(\nu_\mu \rightarrow \nu_e) \neq P(\bar{\nu}_\mu \rightarrow \bar{\nu}_e) $$
  - required for leptogenesis
Questions

- How many neutrino flavors exist?
- What are the squared mass differences?
- What are the absolute neutrino masses?
- Are neutrinos their own anti-particles?
- What are the mixing angles?
- Does neutrino behavior violate CP invariance?
- ...

~ Tokai-to-Kamioka (T2K)
T2K
- Long baseline neutrino oscillation experiment
- JPARC 50GeV proton synchrotron
- Intense $\nu_\mu$ beam
- $E_\nu < 1$GeV
- $L = 295$km
T2K, Phase I – Goals

- Measure **electron neutrino appearance**
  (look for electron neutrinos at far detector)

\[ P(\nu_\mu \rightarrow \nu_e) \approx \sin^2 2\theta_{13} \sin^2 \theta_{23} \]

  ➔ first detection of \( \nu_e \) appearance, or improve upper limit on \( \sin^2 2\theta_{13} \) by factor of 20

- Measure **muon neutrino disappearance**
  (find reduction in muon neutrinos at far detector)

  ➔ Improve precision:

\[ \sin^2 2\theta_{23} \rightarrow \approx \pm 1\% \quad \Delta m_{23}^2 \rightarrow \approx \pm 2\% \]
The Far Detector

Super-Kamiokande III
- 50 kt water Cerenkov detector
- Depth of 1000m (2700mwe)
- 22.5kt fiducial volume
- 11,465 PMTs
- All tubes fixed as of June 2006
- Design beam power 0.77MW
- Proton spills every 3.4s
- Spill width 5.2μs
- $10^{21}$ POT per year (130 days)
Neutrino Beam

\[ p \rightarrow \pi \ X \rightarrow \mu \ \nu_\mu \ X \]

\( E \) tuned to oscillation maximum
Proton beam monitor:

- Measure beam position at target to 1mm
  - Neutrino energy shifts by 2.2MeV / mm
  - Flux shifts by 0.6% / mm
- Measure beam angle to 0.5mrad
  - 0.9m target: 0.5mrad means position shift <0.5mm
  - Measure in combination with proton monitor 3m upstream
- Real time feedback of beam position to accelerator group
... Optical TR Monitor

- Transition radiation emitted when charged particle crosses the boundary of two materials with different permittivity
- Light output: $10^{13}$ photons / pulse
- Readout with optical system

Ray tracing simulation of optics:
- Simulation validated with table top optics system
- Here, shift beam position by 1mm; can reconstruct beam position from the centroid:
OTR NRC test beam

- NRC LINAC (20MeV electrons)
- Scaled version (15%) of actual OTR optics

Obtained detailed images of beam width, position, intensity
ND280 group

- **Canada**
  - UBC, Regina, Toronto, Victoria, TRIUMF, York
- **France**
  - CEA/Saclay
- **Italy**
  - Bari, Napoli, Padova, Rome
- **Japan**
  - Hiroshima, KEK, Kobe, Kyoto, ICRR, Tokyo
- **Korea**
  - Chonnam, Dongshin, Kangwon, Kyungpook, Gyeongsang, Sejong, Seoul, SungKyunKwan
- **Russia**
  - INR Moscow
- **Spain**
  - Barcelona, Valencia
- **Switzerland**
  - Geneva
- **United Kingdom**
  - Imperial, Lancaster, Liverpool, Queen Mary, CCLRC, Sheffield, Warwick
- **United States**
  - Louisiana State, Colorado State, Stony Brook, Rochester, Washington
ND280 Hall

Beam center

SK

37m

Beam

17.5m

On axis detector

Off axis detector

Route area
On axis neutrino detector (NGrid)

- \( E_\nu \) at beam center
- Massive detector
  - Scintillator + iron
  - \( 1m^2 \times 3m \) elements
- Proton beam position with 3mm precision
Off-axis near detector (ND280)

Measure flux and spectrum:

- $\nu_\mu$ in CCQE: $\nu_\mu + n \rightarrow p + \mu^-$  $\Rightarrow \Phi_{\text{near}} \sigma_{\text{CCQE}}$

- backgrounds to CCQE:  $\Rightarrow \sigma_{\text{non-CCQE}} / \sigma_{\text{CCQE}}$

CC1 $\pi^+$: $\nu_\mu + p \rightarrow p + \pi^+ + \mu^-$  NC1 $\pi^+$: $\nu_\mu + p \rightarrow n + \pi^+ + \nu_\mu$

NC1 $\pi^0$: $\nu_\mu + N \rightarrow N + \pi^0 + \nu_\mu$  Beam $\nu_e$ photons ...

- $\nu_e$ flux, spectrum, and cross sections

- CCQE theoretically well understood

Extrapolate to SK with beam MC

A highly segmented large volume detector capable of charged and neutral particle ID and energy measurements.
Off axis ND280

- **UA1 magnet at 0.2 T**

- **Photons and $\pi^0$'s:**
  - Ecal+P0D
  - → Backgds to CCQE

- **Charged particles:**
  - Tracker (TPC+FGD)
  - → Flux and spectrum via CC quasi-elastic

- **Large angle $\mu$'s:**
  - Side MRD
  - → Improve CCQE+bgds
Tracker: FGD

- Measure CCQE:
  - track all charged particles in massive detector
  - Expect 355k CCQE evts for $10^{21}$ POT

- Two modules read out with WLS fibers
  - Plastic scintillator (1.2 t)
  - Plastic scintillator and passive water (0.52 t water)
Tracker: FGD

- Bars will hang in ND basket
- Scintillator bars to be extruded near Vancouver
- Test extrusion successful
- Beam tests underway...
Photo-Sensors

Silicon PM:

- multipixel APD in Geiger mode
- \( \sim 100 - 3000 \) pixel
- High QE, fast response, immune to magnetic fields

- Gain \( \sim 10^6 \)
- Recovery time: \( \sim 100 \text{ns/pixel} \)
- Op. voltage: \( \sim 50 \text{ V} \)
- Noise rate: \( \sim 100-1000 \text{ kHz} \)
Time Projection Chamber

- Gas TPC, $2.5\text{m} \times 2.5\text{m} \times 0.9\text{m}$
- $E$, $B$ fields parallel, perpendicular to beam
- Outer skin at ground
- Purpose:
  - Measure $\vec{p}$ of $\mu$'s produced in CCQE
  - Measure neutrino spectrum
  - Determine charges of reaction products
- Requirements:
  - Momentum resolution $<10\%$
  - Minimize amount of inactive space
TPC Field Cage

- Central Cathode <50kV
- Design resembles STAR field cage
- Potential degrader realized by copper strips on composite walls
- Gas envelope reduces gas contamination, drops high voltage

Excellent field uniformity
Gas Amplification

- Readout using micro-pattern devices

µMEGAS:
First Events in January

Colored by arrival time
Hardware upgrade is necessary for $\geq 1$MW.
Signals at The Far Detector

muon neutrino disappearance:

\[ \sin^2 2 \theta_{23} = 1.0 \quad \Delta m_{23}^2 = 2.7 \cdot 10^{-3} \text{eV}^2 \]
Sensitivity to $\theta_{13}$

- 90% CL contours
- 5 years
- $5 \times 10^{21}$ POT
Summary

- T2K I to improve measurement of $\theta_{13}$ and of atmospheric oscillation parameters
- CP violation in phase II
- Superkamiokande rebuilt
- Near detector R&D in good shape
  - OTR observed with scaled OTR prototype
  - FGD design well advanced, extrusion run of scintillators successful, beam tests underway
  - TPC prototype in operation since January
Extras
The OTR Team
Side muon range detector (SMRD)

Active component:
- Extruded scintillator (87 x 17 x 1 cm$^3$)
- Light collected with WLS shifting fiber
- Read out by Silicon PMs on both sides

Measure large angle muons
Electromagnetic calorimeter

- **Purpose**
  - Energy detection around P0D
  - Pi0 recon. around tracker
  - Charged particle ID

- **Barrel ECAL (10.3X₀):**
  - 25 scintillator layers (4cm x 1cm)
  - Pb layers interleaved

- **Downstream ECAL (11.6X₀):**
  - 29 scintillator layers (4cm x 1cm)
  - Pb layers interleaved
Pi Zero Detector – P0D

For high statistics measurements of e+m showering particles.

- scintillating bar tracking planes
- front section interleaved with 1.7 tonnes of passive water layers

⇒ statistical subtraction of events in rear from front used to determine oxygen cross sections
Intermediate detector @ 2km

- $E_\nu$ spectrum @ 2km ~ $E_\nu$ spectrum @ SK w/o oscillation
  → Uncertainties from Far/Near ratio are smaller than wrt ND280m.
- Liquid Ar TPC + Water Cherenkov + Muon Range Detector
  - Very similar $\nu$ detection to SK
    … Reduce systematic uncertainties.
  - Excellent Tracking by LAr-TPC
    … Precise measurement of $\nu$-nucleus interactions.

The experimental facility for 2km detector is not approved yet.
Sensitivity to $\theta_{13}$
FGD Design Details
A TPC's Field Cage

• **Accurate** tracking requires **uniform electric field**

\[ V(x) = E \times x \]

• Approximate continuous field cage with discrete grid

Field cages used by

• **ALICE**
  • suspended mylar strips (aluminized)

• **STAR**
  • edged copper on Kapton

• ...
Wall Construction

- Composite Wall
  - 0.02mm Copper
  - 1mm G10
  - 10mm Rohacell
- 2.84% radiation length
- Grooves define strips
  - Cut with router
  - Reduce impact of surface charges
ND280 – TPC: Gas choice

- Many space points along the track (90 e⁻/cm)
- Minimize diffusion (D < 260μm/(cm)\(^{1/2}\))
- Slow gas acceptable b/c 3.5s btw spills

✔ low diffusion, insensitive to E×B distortions and 5μs spill width
✗ electron attachment on O₂

![Graphs showing Drift Velocity and Transverse diffusion for different gas mixtures.](image)
Tracker – FGD and TPC

Study reactions that produce charged particles:

- $\nu_\mu$ CC quasi-elastic (CCQE) scattering to measure the $\nu_\mu$ flux and spectrum prior to oscillation
- $\nu_\mu$ CC in-elastic scattering that can be misinterpreted by SK as CCQE, thus assigning an incorrect $\nu_\mu$ energy
- $\nu_\mu$ NC in-elastic scattering that produce $\pi^+$ and $\pi^-$ which can be misinterpreted by SK to be CCQE
- $\nu_e$ CCQE scattering to determine the $\nu_e$ flux and spectrum, a main background to $\nu_e$ appearance at SK
The Off Axis Near Detector (ND280)

Requirements:

- Operate in “high” neutrino rate environment
- Measure neutrino beam before oscillation
  - Muon neutrino flux and spectrum
  - Electron neutrino flux and spectrum
- Measure neutrino interactions and cross sections
  - Understand processes at SuperK

☞ A highly segmented large volume detector capable of charged and neutral particle energy measurements and particle identification