T2K near detector upgrade & Hyper-Kamiokande project

Masashi Yokoyama
Department of Physics, The University of Tokyo
T2K: ND280 upgrade convener & Executive Committee
Hyper-K: Physics Coordinator & Steering Committee
May 15, 2017 @ IoP Bhubaneswar
Breaking results from T2K

First ever measurement of leptonic CP asymmetry; Already hint of possible large CPV!!

Results from reactor experiments
T2K-II extension

- Proposal to accumulate 20E21 POT (1/30 g of protons!) by 2025-2026
- With increased beam power of J-PARC
- >3\sigma sensitivity for CP violation for favorable parameters
Need for precision

- In the standard framework, expected difference between $\nu$ and anti-$\nu$ is $\sim\pm25\%$ at maximum
- A few % uncertainty is necessary for measurement
- Large statistics and control of systematics are crucial
  - Statistics $\rightarrow$ beam power increase, additional samples
  - Systematics $\rightarrow$ *neutrino interaction*, hadron interaction

Systematic uncertainty of $\nu_e$ events at SK (goal at proposal: $<10\%$)

$9.9\%(2012) \rightarrow 8.8\%(2013) \rightarrow 6.8\%(2014) \rightarrow 5.4\%(2016)$

Goal for T2K-II systematics: $\sim4\%$ in total
Neutrino interaction

- Properties of neutrinos are derived from measurement of final state particles in interaction with nucleus

- Complicated because of nucleus structure and hadronic interactions

→ source of one of major systematic uncertainties
Neutrino interaction in T2K

Charged current (CC) quasi-elastic (QE)
\[ \nu + n \rightarrow \mu/e + p \]
- Largest cross section in \( \sim < 1 \text{GeV} \)
- Energy reconstruction with lepton kinematics
  - \( E_\nu \) reconstructed assuming CCQE in T2K

CC single pion production
\[ \nu + p(n) \rightarrow \mu/e + n(p) + \pi^\pm \]

NC single pion production
- \( \pi^+ \): BG in \( \nu_\mu \) disappearance
- \( \pi^0 \): BG in \( \nu_e \) appearance

Multi-pion production

++ Nuclear effects

Cross-sections

- CC Total
- CC quasi-elastic
- DIS
- NC single \( \pi^0 \)
- NEUT MC simulator

\[ \sigma/E \times 10^{-38} \text{cm}^2/\text{GeV} \]

\( E_\nu \) (GeV)

Total (NC+CC)

Q2P + n \( \rightarrow \) Q2P - n + p
Q2P + N \( \rightarrow \) Q2P + N' + \( S_\text{(K,K)} \)

Q2P + N \( \rightarrow \) Q2P + X' + m \( S_\text{(K,K)} \)

(\( l \): lepton, \( N, N' \): nucleon, \( m \): integer)
“Near” detectors

- “Smaller” detectors at J-PARC (~280m downstream) to characterize neutrinos just after production (before neutrino oscillation)
- Reduce systematic errors
• Excellent performance as designed
  • Fine Grained Detector (FGD) with carbon and oxygen (water) targets
  • TPC for charge, momentum, and PID
  • Calorimeter coverage
  • Inside UA1 magnet (B=0.2T)
• Weak for high angle and backward tracks
  • When designed, emphasis was on background and forward-going tracks
  • With the large value of $\theta_{13}$, signal becomes more important
Systematic uncertainty for $E_{\nu}^{\text{rec}}$ @ SK

μ-like sample

e-like sample

Systematics controlled by near detector data
ND280 upgrade for T2K-II

- Plan to upgrade ND280 in order to reduce systematics
- Extend angular acceptance with new target detectors and new TPCs
- Configuration under optimization

Neutrino beam direction

![Diagram showing the upgrade of ND280 with new TPCs and target detectors.]
Possible configurations

One of reference configurations under study
New detectors  Relocate existing TPCs

One of alternative configurations
New detectors  Keep TPCs and FGDs

Design study intensively ongoing
TPCs

- Requirements similar to existing T2K TPCs

Several possibilities of improvement: resistive bulk micromegas, thinner field cage, .. to be studied
Target detector

- Baseline technology: plastic scintillator + wavelength shifting fiber + MPPC (SiPM)
- Well established in T2K near detectors
- New version of MPPCs with better performance, other improvement also to be studied
Target detector

• Provide target mass for neutrino interaction
  • Especially important for $\nu_e$ measurement
  • Water target necessary or not?
• Acceptance for large angle tracks
• Reconstruct tracks inside detector
• Background reduction/control for $\nu_e$ measurement

3D-FGD

The 3-axis structure

By repeating this structure and close-packing them as shown on the previous page, you can get 75% fill ratio (25% of volume is air)

New target tracker

- Target gets sandwiched by very thin electrode.
- MPGD’s are supported by target.

NOTE: This figure shows just a small part of the whole detector. All components are contained in one gas container.

3D-FGD

Still several concepts: selection in ~half year
Forming the project

- T2K officially launched ND upgrade project after a few years of internal discussion
- Aim to become also project at CERN Neutrino Platform, submitted Expression of Interest
- Having workshops (open to non-T2K people)
  - 1st/2nd meetings held at CERN
    https://indico.cern.ch/event/568177/, https://indico.cern.ch/event/613107/
  - 3rd one at J-PARC, next weekend (May 20/21)
    https://indico.cern.ch/event/633840/
- In the process of defining Work Packages, design & responsibilities
ND280 upgrade timeline

• **2017**: optimization studies, define configuration, finalize responsibilities, write proposals

• **2018**: Prototype and test, fix detector parameters (granularity etc.)

• **2019-20**: Production, integration, system test

• **2021 summer**: installation and commissioning

Still in an early stage of project — new partners are very welcome!
Other R&D activities in J-PARC

- Many test projects and R&D in J-PARC

3D grid structure of scintillator for large angle tracking (WAter Grid And SCIntillator, “WAGASCI”)

- First test module installed last summer
- More module under construction

Graduate students leading the project!

Real event

Jay Vora from IITB worked for construction
Nuclear emulsion technique (Neutrino Interaction research with Nuclear emulsion and J-parc Accelerator, “NINJA”)

- Excellent (<μm) spatial resolution for ν interaction study
- Data with small module being analyzed
- Staged approach to larger experiment

Water Cherenkov Detectors

- Utilize different off-axis angles to sample different energy spectrum (“NuPRISM”)
- At 1-2km from target
- Also considered as a near detector for Hyper-K, merged with another proposal with Gd loading (“TITUS”)

Fig. 22
Three-dimensional view of neutrino candidate events. Neutrino beam direction is parallel to the z-axis.

Fig. 23
Impact Parameter and Emission angle for MIP and black tracks.
Opportunities for discovering CPV in lepton sector

CPV significance for $\delta=-90^\circ$, normal hierarchy

Seamless program of Japan-based experiments

$\sim 3\sigma$ indication with T2K $\rightarrow$ T2K-II, $>5\sigma$ discovery and measurement with HK
Fiducial mass:
Super-Kamiokande × 20
↓
100 years in SK = 5 years in HK
Better performance with improved photo-sensors
Three generations of K

Kamiokande (1983-1996)

Super-Kamiokande (1996-)

Hyper-Kamiokande (202x-)

- 186 kton detector volume
- Opcally separated into 40,000 PMTs

- ID Photosensors will be high QE
- Single photon detection: 24%

- Receive 1.3 MW beam from J-PARC
- Accumulate 2.7 × 10^22 POT

- Multipurpose machine, all of the physics of Super-K and T2K plus more! Geophysics
- Accessible only with very large detectors

- Not just a larger version of Super-K
- Improved performance: photosensors, tank materials

- 60 m 74 m

- Staged design: 186 kton in 6 years, 372 kton thereafter

- ?
Broad science program with Hyper-K

- Neutrino oscillation physics
  - Comprehensive study with beam and atmospheric neutrinos
- Search for nucleon decay
  - Possible discovery with \( \sim \times 10 \) better sensitivity than Super-K
- Neutrino astrophysics
  - Precision measurements of solar \( \nu \)
  - High statistics measurements of SN burst \( \nu \)
  - Detection and study of relic SN neutrinos
- Geophysics (neutrino seismology of interior of the Earth)
- Maybe more (unexpected)

\[ \begin{align*}
\text{MeV} & \quad \text{TeV} \\
\text{Solar} & \quad \text{Supernova} \\
\text{Accelerator} & \quad \text{Proton decay} \\
\text{DM search} & \quad \text{Atmospheric}
\end{align*} \]

\[ \begin{align*}
\sim 3.5 \text{MeV} & \quad \sim 20 \text{MeV} & \quad \sim 100 \text{MeV} & \quad \sim 1 \text{GeV} & \quad \text{TeV}
\end{align*} \]
Well proven, scalable technique

- Feasibility of ~Mton size detector confirmed with various studies over past decade
- 20 years experience with Super-Kamiokande
- “Ready-for-construction” design developed
Long baseline experiment

Hyper-Kamiokande

Super-Kamiokande

Hint from T2K experiment

Higher intensity beam from J-PARC + Hyper-Kamiokande
Definite measurement

Closing in on the origin of matter in Universe
Strength of HK long-baseline program

- Best sensitivity for CP measurement
- Relatively short baseline (~300km): less matter effect
- Off axis beam at 1st oscillation maximum
- Large statistics with good S/N
  - ~2000 appearance signal events expected
  - S/N~10 at appearance peak
- Performance proven with real data
- Building on experience from T2K/Super-K
- Further improvement expected with T2K/T2K-II
Expected events

1.3MW, $10 \times 10^7$sec, $\nu:\overline{\nu}=1.3$

$\nu_e$ candidates

Using fiTQun for $\pi^0$ rejection

<table>
<thead>
<tr>
<th>for $\delta=0$</th>
<th>Signal $(\nu_{\mu} \rightarrow \nu_e \text{ CC})$</th>
<th>Wrong sign appearance</th>
<th>$\nu_{\mu}/\overline{\nu}_{\mu}$ CC</th>
<th>beam $\nu_e/\overline{\nu}_e$ contamination</th>
<th>NC</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\nu$ beam</td>
<td>2,300</td>
<td>21</td>
<td>10</td>
<td>362</td>
<td>188</td>
</tr>
<tr>
<td>$\overline{\nu}$ beam</td>
<td>1,656</td>
<td>289</td>
<td>6</td>
<td>444</td>
<td>274</td>
</tr>
</tbody>
</table>

$\delta=0$ and $180^\circ$ can be distinguished using shape information
CPV sensitivity

- Exclusion of $\sin\delta_{CP}=0$
  - $>8\sigma(6\sigma)$ for $\delta=-90^\circ(-45^\circ)$
  - $\sim80\%$ coverage of $\delta$ parameter space with $>3\sigma$
- From discovery to $\delta_{CP}$ measurement:
  - $\sim7^\circ$ precision possible

<table>
<thead>
<tr>
<th>$\sin\delta=0$ exclusion</th>
<th>error</th>
</tr>
</thead>
<tbody>
<tr>
<td>$&gt;3\sigma$</td>
<td>$&gt;5\sigma$</td>
</tr>
<tr>
<td>$78%$</td>
<td>$62%$</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>$\delta=0^\circ$</th>
<th>$\delta=90^\circ$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$7.2^\circ$</td>
<td>$21^\circ$</td>
</tr>
</tbody>
</table>

Diagram:
- Normal mass hierarchy
  - $\sin^2\theta_{13}=0.1$
  - $\sin^2\theta_{23}=0.5$

- HK 2tank staging 10 years

Graphs:
- Error vs. Running time
- $\delta_{CP}=90^\circ$ vs. $\delta_{CP}=0^\circ$
CPV sensitivity

- Exclusion of $\sin \delta_{\text{CP}} = 0$
  - $>8\sigma (6\sigma)$ for $\delta = -90^\circ (-45^\circ)$
  - ~80% coverage of $\delta$ parameter space with $>3\sigma$

- From discovery to $\delta_{\text{CP}}$ measurement:
  - ~7° precision possible

<table>
<thead>
<tr>
<th>$\sin \delta = 0$ exclusion</th>
<th>error</th>
</tr>
</thead>
<tbody>
<tr>
<td>$&gt;3\sigma$</td>
<td>$&gt;5\sigma$</td>
</tr>
<tr>
<td>78%</td>
<td>62%</td>
</tr>
<tr>
<td>$\delta = 0^\circ$</td>
<td>$\delta = 90^\circ$</td>
</tr>
<tr>
<td>7.2°</td>
<td>21°</td>
</tr>
</tbody>
</table>

Excellent sensitivity for CPV
Proton decay searches

- Only way to directly probe Grand Unified Theory which unifies interactions at very high energy
- Two major modes predicted by many models

\[
p \rightarrow e^+ \pi^0 \quad \Gamma(p \rightarrow e^+ \pi^0) \sim \frac{g^4 m_5}{M_p^4} \\
p \rightarrow \nu K^+ \quad \Gamma(p \rightarrow \nu K^+) \sim \frac{\tan^2 \beta \times m_5}{M_2^2 \times M_3^2}
\]

- Need broad searches including other possible modes
\[ p \rightarrow e^+ \pi^0 \]

- Can be fully reconstructed
- Kinematic selection
- \( M_{\text{tot}} \sim m_p, p_{\text{tot}} \sim 0 \)
- Clear signal can be seen for lifetime above the current limit
- Negligible background in the free proton enhanced region
- Atm. \( \nu \) BG suppression by neutron tagging (thanks to higher photon yield)

For \( \tau p/Br = 1.7 \times 10^{34} \) years

HK 10 years MC

For \( 0 < P_{\text{tot}} < 100 \text{MeV/c} \)

Proton mass peak

For \( 100 < P_{\text{tot}} < 250 \text{MeV/c} \)
$p \rightarrow e^+ \pi^0$ sensitivity

$3\sigma$ discovery potential will reach $\sim 10^{35}$ years!
$p \rightarrow e^+ \pi^0$ sensitivity

$\tau / \beta$ [years]

$\sigma$ HK 560 kton LD , $3\sigma$
$\sigma$ HK 186 kton HD , $3\sigma$
$\sigma$ LAr 40kton , $3\sigma$
$\sigma$ HK 372 kton HD staged , $3\sigma$

$3\sigma$ discovery potential will reach $\sim 10^{35}$ years!
\( p \rightarrow \bar{\nu}K^+ \) sensitivity

- Clear signal can be seen for lifetime beyond the current limit

For \( \tau_p/\text{Br} = 6.6 \times 10^{33} \) years

HK 10 years MC

\( P_{\mu} \) for \( K \rightarrow \mu \nu \)

\( K \rightarrow \pi\pi \)

In 10 years, \( 3\sigma \) discovery sensitivity \( 2.5 \times 10^{34} \) years
(Answering to earlier question)

**LIMIT ON $n\bar{n}$ OSCILLATIONS**

**Mean Time for $n\bar{n}$ Transition in Vacuum**

A test of $\Delta B=2$ baryon number nonconservation. MOHAPATRA 80 and MOHAPATRA 89 discuss the theoretical motivations for looking for $n\bar{n}$ oscillations. DOVER 83 and DOVER 85 give phenomenological analyses. The best limits come from looking for the decay of neutrons bound in nuclei. However, these analyses require model-dependent corrections for nuclear effects. See KABIR 83, DOVER 89, ALBERICO 91, and GAL 00 for discussions. Direct searches for $n \rightarrow \pi$ transitions using reactor neutrons are cleaner but give somewhat poorer limits. We include limits for both free and bound neutrons in the Summary Table. See MOHAPATRA 09 for a recent review.

<table>
<thead>
<tr>
<th>VALUE (s)</th>
<th>CL%</th>
<th>DOCUMENT ID</th>
<th>TECN</th>
<th>COMMENT</th>
</tr>
</thead>
<tbody>
<tr>
<td>$&gt;2.7 \times 10^8$</td>
<td>90</td>
<td>ABE</td>
<td>15C</td>
<td>CNTR n bound in oxygen</td>
</tr>
<tr>
<td>$&gt;8.6 \times 10^7$</td>
<td>90</td>
<td>BALDO-...</td>
<td>94</td>
<td>CNTR Reactor (free) neutrons</td>
</tr>
<tr>
<td>$&gt;1.3 \times 10^8$</td>
<td>90</td>
<td>CHUNG</td>
<td>02B</td>
<td>SOU2 n bound in iron</td>
</tr>
<tr>
<td>$&gt;1 \times 10^7$</td>
<td>90</td>
<td>BALDO-...</td>
<td>90</td>
<td>CNTR See BALDO-CEOLIN 94</td>
</tr>
<tr>
<td>$&gt;1.2 \times 10^8$</td>
<td>90</td>
<td>BERGER</td>
<td>90</td>
<td>FREJ n bound in iron</td>
</tr>
<tr>
<td>$&gt;4.9 \times 10^5$</td>
<td>90</td>
<td>BRESSI</td>
<td>90</td>
<td>CNTR Reactor neutrons</td>
</tr>
<tr>
<td>$&gt;4.7 \times 10^5$</td>
<td>90</td>
<td>BRESSI</td>
<td>89</td>
<td>CNTR See BRESSI 90</td>
</tr>
<tr>
<td>$&gt;1.3 \times 10^8$</td>
<td>90</td>
<td>TAKITA</td>
<td>86</td>
<td>CNTR n bound in oxygen</td>
</tr>
<tr>
<td>$&gt;1 \times 10^6$</td>
<td>90</td>
<td>FIDECARO</td>
<td>85</td>
<td>CNTR Reactor neutrons</td>
</tr>
<tr>
<td>$&gt;8.8 \times 10^7$</td>
<td>90</td>
<td>PARK</td>
<td>85B</td>
<td>CNTR</td>
</tr>
<tr>
<td>$&gt;3 \times 10^7$</td>
<td>90</td>
<td>BATTISTONI</td>
<td>84</td>
<td>NUSX</td>
</tr>
<tr>
<td>$&gt; 0.27–1.1 \times 10^8$</td>
<td>90</td>
<td>JONES</td>
<td>84</td>
<td>CNTR</td>
</tr>
<tr>
<td>$&gt;2 \times 10^7$</td>
<td>90</td>
<td>CHERRY</td>
<td>83</td>
<td>CNTR</td>
</tr>
</tbody>
</table>

Super-Kamiokande gives the best limit for $n-n\bar{n}$ oscillation
International R&D ongoing

- Intense R&D work over the world
- Photo-sensor, calibration, electronics, DAQ, software, physics sensitivity studies…
### Hyper-K construction timeline

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

- **Assuming construction funding from 2018**
- **The 1st detector construction in 2018~2025**
  - Cavern excavation: ~5 years
  - Tank (liner, photosensors) construction: ~3 years
  - Water filling: 0.5 years

---

- Photosensor development
- Suvey, detailed design
- Access tunnels
- Cavity excavation
- Tank construction
- Sensor installation
- Water filling
- Operation

Beam up to 1.3MW
• International Proto-Collaboration formed in 2015
• Currently ~300 members from 15 countries
• Selected as one of 28 highest priority projects among all science projects by Science Council of Japan
• Set as highest priority future projects by ICRR and KEK
• Budget request for construction under preparation by U. Tokyo
• Formation of new institution,
Conclusions

• World-leading physics opportunities in neutrino program in Japan
  • Neutrino CPV, precision measurements, exotic searches …
• Lots of activities with international collaboration
  • T2K-II upgrade
  • Hyper-K preparation
  • Additional R&D efforts
• New collaborators are always welcome!
• Now is particularly good time as we are starting new initiatives (T2K-II, Hyper-K)!