ГиперКамиоканаде и DUNE

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ИЯИ РАН
Main goals:
- Search for CP violation
- Proton decay
- Neutrino astrophysics

Hyper-K water tank

Water tank
60 m(H)x74m(D)
Total volume 260 kt
Fiducial volume 190 kt ~10xSuper-K
40000 50 cm ID PMTs PMT coverage 40%
6700 20 cm OD PMTs
Photon sensitivity ~2 times better than Super-K
Construction of 2nd tank in Korea
(1-3 deg off axis, 2nd oscill. maximum) is under study

J-PARC

12 countries
> 350 collaborators
Water tank

Total: 258.1 kt/tank
Inner Detector: 215.7 kt/tank
Fiducial Volume: 187.0 kt/tank

ID surface area: 20,063 m²
1 ID-PMT/0.5m² (40% coverage)
→ ~40,000 ID-PMTs/tank
~6,700 OD-PMTs/tank
Photosensors

Hamamatsu R12860-HQE
B&L 50 cm PMT

40000 PMTs
40% photocoverage

Other 50-cm candidates:
- Hybrid Photo-Detector
- MCP PMT
- Multi-PMT

1 p.e. time resolution 1.1 ns
charge resolution 35%

Hamamatsu R5912-HQE
B&L 20 cm PMT
Tokai-to-Hyper-K (T2HK)

Hyper-K

J-PARC

L = 295 km

Off-axis neutrino beam

Neutrino monitor INGRID

Off-axis near neutrino detector

Decay tunnel

Horn

Target

Neutrino beam elements

J-PARC neutrino beam

2.5° off-axis, peak energy 600 MeV (oscillation maximum), current beam power 485 kW
Physics

Accelerator neutrinos
- search for CP violation
- precise measurement of oscillation parameters

Atmospheric and solar neutrinos
- mass hierarchy
- $\theta_{23}$ octant

Nucleon decays

Neutrino astronomy and astrophysics
Search for CP violation

Hint on maximal CP violation, $\delta \sim -\pi/2$, $\delta = 0$ excluded at 2$\sigma$

$E = 0.6$ GeV, $\Delta m^2_{32} L/4E \approx 1$

$A_{CP} =$

T2HK
for $\delta = -\pi/2$
$\rightarrow$ CP violation effect $A_{CP} \sim 28$
$\rightarrow$ matter effect $\sim 8$

NOvA

$\Rightarrow$ Search for CP violation
Sensitivity to CP

\[ \nu : \bar{\nu} = 1:3 \quad \sin^2\theta_{13} = 0.1 \]

Integrated beam power 1.3 MW x 10^8 s
\[ \rightarrow 2.7 \times 10^{22} \text{ POT with 30 GeV proton beam} \]

T2HK: uncertainties of expected number events

- \( \nu_\mu \rightarrow \nu_e \) 3.2%
- \( \nu_\mu \rightarrow \nu_\mu \) 3.6%
- \( \bar{\nu}_\mu \rightarrow \bar{\nu}_e \) 3.9%
- \( \bar{\nu}_\mu \rightarrow \bar{\nu}_\mu \) 3.6%

Exclusion of \( \delta=0 \) at 8\( \sigma \) (for \( \delta=-\pi/2 \))
5\( \sigma \) (3\( \sigma \)) significance for 57 (80)% of possible \( \delta \) values
Prospects for $\delta$ measurements

Measurement of $\delta$

$\delta = 90$ deg $\quad \sigma = 23$ deg
$\delta = 0$ deg $\quad \sigma = 7$ deg
J-PARC upgrade

1.3MW by Hyper-K

485 kW achieved

J-PARC 30 GeV main ring

→ 750 kW (cycle 1.3 s) - 2020

→ 1.3 MW (cycle 1.16 s) - 2026

Narrow-band neutrino beam, peak energy 600 MeV
**ND280 upgrade**

**E61: Movable Water Cherenkov detector**
- Inner diameter 8 m
- Inner detector height 6-8 m
- Multi-PMTs
- Load detector with Gd$_2$(SO$_4$)$_3$ to enhance neutron detection

**New upstream tracker:**
- Two Horizontal TPCs
- One 3D fine-grained scintillator target SuperFGD
- TOF system around new tracker

Measurement of neutron multiplicity to understand Gd n-capture signal in Super-K and Hyper-K

3D highly granular scintillator detector (SuperFGD):
- Precise measurement of neutrino energy;
- Cover full solid angle and low momentum for charged particles from neutrino interactions;
- Measure electron neutrino cross sections;
- Measure nuclear effects in neutrino interactions;
- Reduce systematic uncertainties to 3-4% level in oscillation measurements
SuperFGD

- Volume 200 x 200 x 60 cm$^3$
- $2 \times 10^6$ scintillator cubes, 1 x 1 x 1 cm$^3$
- Each cube has 3 holes, diameter 1.5 mm
- 3D (x,y,z) WLS readout
- About 60000 readout WLS/MPPC channels
- Total active weight about 2 t

Fully active, highly granular, $4\pi$ scintillator neutrino detector with 3D WLS/MPPC readout

MC simulation

electron

photon
Technology

Cubes are manufactured at Uniplast, Vladimir

Extrusion $\rightarrow$ injection molding

New machine for injection molding was bought and commissioned at Uniplast in July 2018

Assembly, mechanics, tests, fibers, photosensors .... at INR

Precision: each side $\leq 30 \, \mu m$
Beam tests at CERN

T9 channel at CERN: muons, pions, protons, electrons 0.5 – 5.0 GeV

-First small prototype:
  -125 cubes, 75 readout channels
  -Beam test October 2017

Large prototype

Length 48 cm
Width 24 cm
Height 8 cm
9216 cubes, each 1x1x1 cm³
1728 Y11 WLS fibers, 1 mm diameter
Readout: 1728 MPPC’s

2 beam tests:
  June-July 2018
  August-September 2018
Beam events

Top views

Positron, 1 GeV, B = 0.2 T

Muon, 5 GeV, 45 deg

Stopped proton, 0.5 GeV, 45 deg
Results

MIP: Light yield per fiber

- Light yield of 1 cube/1 fiber: 42 p.e./MIP
- Light yield of 1 cube/2 fibers: 80 p.e./MIP

MIP: time resolution per fiber

- 1 fiber: 0.92 ns
- 1 cube/2 fibers: 0.68 ns
- 2 cubes/4 fibers: 0.48 ns
- 3 cubes/6 fibers: 0.39 ns
Schedule for SuperGFD

Manufacturing of detector elements          01.2019 - 12.2020
Assembly                                          10.2020 – 09.2021
Tests                                              07.2021 – 09.2021
Installation into ND280 pit                            10.2021

Participants :
INR; KEK, U.Tokyo, U.Kyoto; U.Geneva, CERN;
Ecole polytechnique, Saclay; Uppsala;
NCBJ, Warsaw; LSU, Stony Brook
Status of Hyper-K and T2HK

Official statement, 12 September 2018

- Seed funding for Hyper-Kamiokande construction was allocated within MEXT 2019 budget

- The University of Tokyo pledges to ensure construction of Hyper-Kamiokande in April 2020
T2HKK

2nd Hyper-K detector in Korea

T2HKK = Tokai-to(2)-HK-to-Korea

KNO
Korean Neutrino Observatory

1-3 deg. off-axis

The J-PARC \( \nu \) beam comes to Korea.

\( L = 1000-1200 \text{ km} \)
**Main goals:**
- discovery of CP violation in leptonic sector
- neutrino mass hierarchy at >5\(\sigma\) level
- neutrino astronomy
- proton decay search

**Beam power**
- \(E_p = 60-120\) GeV
- Beam power 1.2 -> 2.4 MW

**On axis neutrino beam**
- \(E_\nu \sim 1-6\) GeV
- L=1300 km from FNAL to SURF, S.Dakota

**LBNF/DUNE project**
- Flagship FNAL project
- 30 countries
- 161 institutions
- > 1000 collaborators

**Far detector**
- 40 kt (4 x 10kt) LAr TPC

**Sensitivity to CP violation**

**Timeline**
- 2021 – installation of 1\(^{st}\) far detector
- 2024 – 2 modules operational
- 2026 – deliver neutrino beam
Detector prototyping

Detector R&D of LAr detectors within the CERN neutrino platform start in 2016 beam in 2018

Both prototypes are installed at CERN, in a dedicated extension of the North Area.
1st 10 kt module of DUNE - single-phase TPC
6m x 2.3 m anode and cathode planes 3.6 m spacing
Photon detectors – light guides + SiPMs embedded in APAs
Dual Phase TPC

NP02: WA105 (DP demonstrator + ProtoDUNE DP)

Demonstrator: 3x1x1 m³ – 5 tons

ProtoDUNE DP: 6x6x6 m³
300 tons active mass

Measurements with test beam in 2018
First events in SP TPC

21/09/2018: First track seen at nominal E Field!

On-line Event Display

02/10/2018: First pion interaction from beam!
(1 GeV pion)

DQM Event Display
DUNE Near Detector

3DST: A few ton segmented scintillator detector. Similar to SuperFGD
T2HK and DUNE: CPV Significance

Hyper-K
- Single tank
- Normal hierarchy
- Systematics 3-4%
  \[ \nu : \nu = 1:3 \]
- CPV (\(\delta = -90\) deg, 5\(\sigma\))
  \[ \rightarrow 1.3\text{MW} \times 4\text{ years} \]

DUNE
- Staging plan
- Normal hierarchy
  \[ \nu : \nu = 50\%:50\% \]
- CPV (\(\delta = -90\) deg, 5\(\sigma\)) 253 kt\(\cdot\)MW\(\cdot\)year
  \[ \rightarrow 6.5\text{ years} \]

Combination T2K-II and NOvA can reach 4.0-4.5\(\sigma\) for \(\delta = -90\) deg by 2026
Nucleon Decay sensitivities

The diagram illustrates the sensitivities of various experiments to nucleon decay predictions. The horizontal axis represents the lifetime of the particle in years (τ/B), and the vertical axis indicates the predictions for specific decay modes involving proton and antineutrino decays. The experiments mentioned include Soudan, Frejus, Kamiokande, IMB, Super-K, Hyper-K, KamLAND, JUNO, and Hyper-K. The decay modes shown are

- $p ightarrow e^+ \pi^0$
- $p ightarrow e^+ K^0$
- $p ightarrow \mu^+ K^0$
- $n ightarrow \bar{\nu} K^0$
- $p ightarrow \bar{\nu} K^+$

Each experiment has a region where it is sensitive to these decays, indicated by the star symbols. The background colors represent different supersymmetric (SUSY) models, with yellow for SUSY SO(10) and orange for non-SUSY SO(10) G224D. The red star indicates the current sensitivity of Hyper-K, while the blue star represents the sensitivity of Super-K.
Hyper-Kamiokande and DUNE - the major next generation neutrino experiments

Very broad physics program:
- search for CP violation in neutrino oscillations
- proton decay
- rich program with atmospheric and solar neutrinos
- supernova neutrinos
- + other interesting physics

Detector (Far and Near) R&D and upgrade in progress → good results

Experiments are expected to start data taking in 2026
Backup slides
Assumed proton lifetime

\[ \tau_p/Br = 1.7 \times 10^{34} \text{ years} \]

Free proton bin

Bound proton bin

Hyper K, 1 tank, 10 year exposure

\[ p \rightarrow e^+ \pi^0 \text{ events} \]
\( \nu_e \) and \( \bar{\nu}_e \) events

1 Hyper-K tank, 1.3MW, 10x10^7 sec, \( \nu : \text{anti-}\nu = 1:3 \), \( \sin^2 2\theta_{13} = 0.1 \)

\[ \delta = 0 \text{ deg} \]

<table>
<thead>
<tr>
<th>( \delta = 0 \text{ deg} )</th>
<th>Appearance signal</th>
<th>Wrong sign</th>
<th>Beam ( \nu_e ) background</th>
<th>NC background</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \nu ) mode</td>
<td>1643</td>
<td>15</td>
<td>259</td>
<td>134</td>
</tr>
<tr>
<td>anti-( \nu ) mode</td>
<td>1183</td>
<td>206</td>
<td>317</td>
<td>196</td>
</tr>
</tbody>
</table>
T2HKK: $\delta$ precision

T2HKK: study oscillations at 1\textsuperscript{st} and 2\textsuperscript{nd} oscillation maxima
→ better sensitivity to mass hierarchy
→ better sensitivity to CP violation

JD x 1: HK 1 tank, Japan
$\sigma(\delta) = 22$ deg

JD x 2: HK 2 tanks, Japan
$\sigma(\delta) = 17$ deg

JD + KD: HK 1 tank (Japan + HK 1 tank (Korea))
$\sigma(\delta) = 13$-14 deg
Proton Decay: $p \rightarrow \pi^0 e^+$

GUT predicts this process through gage bosons

$$\Gamma(p \rightarrow e^+ \pi^0) \sim \frac{1}{M_X^4} \quad \tau_p \sim \frac{M_X^4}{m_p^5}$$

Neutron tagging

$$(n+p \rightarrow d+\gamma, E_\gamma=2.2\text{MeV})$$

helps to reduce background
Proton Decay: $p \rightarrow \bar{\nu} K^+$

Supersymmetric GUTs

Assumed proton lifetime
\[ \tau_p/\text{Br} = 6.6 \times 10^{33} \text{ years} \]

1 tank, 10 year exposure

M. Shiozawa, Neutrino2018