Neutrino detectors for oscillation experiments

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OUTLINE

- Neutrino oscillations
- Current experiments
  - Accelerators: T2K, NOVA
  - Plans for upgrade
  - Reactors: Daya Bay, RENO, Double Chooz

- Future projects
  - JUNO
  - DUNE
  - HyperKamiokande
Talks

W. H. Trzaska
WA105 experiment at CERN: large demonstrator of Dual Phase Liquid Argon TPC detector for DUNE

V. Berardi
The Hyper-Kamiokande detector: R&D studies of a new generation of Photosensors

Y. Heng
The Instrumentation of JUNO

Posters

I. Anfimov
Testing methods for 20 inches PMTs of the JUNO experiment

Z. Wang
JUNO PMT system

A. Mefodiev
B. Developing of segmented neutrino detector Baby-MIND
**ν oscillations and mixing**

**Standard Model:** neutrinos are *massless* particles

3 families

\[
\begin{pmatrix}
  \nu_e \\
  \nu_\mu \\
  \nu_\tau
\end{pmatrix} = U
\begin{pmatrix}
  \nu_1 \\
  \nu_2 \\
  \nu_3
\end{pmatrix}
\]

*U* parameterization:

- three mixing angles \( \theta_{12} \), \( \theta_{23} \), \( \theta_{13} \)
- CP violating phase \( \delta_{CP} \)

atmospheric

\[
\begin{pmatrix}
  \nu_e \\
  \nu_\mu \\
  \nu_\tau
\end{pmatrix} =
\begin{pmatrix}
  1 & 0 & 0 \\
  0 & \cos \theta_{23} & \sin \theta_{23} \\
  0 & -\sin \theta_{23} & \cos \theta_{23}
\end{pmatrix}
\begin{pmatrix}
  \nu_1 \\
  \nu_2 \\
  \nu_3
\end{pmatrix}
\]

link between atmospheric and solar

\[
\begin{pmatrix}
  \cos \theta_{12} & \sin \theta_{12} & 0 \\
  -\sin \theta_{12} & \cos \theta_{12} & 0 \\
  0 & 0 & 1
\end{pmatrix}
\begin{pmatrix}
  \nu_1 \\
  \nu_2 \\
  \nu_3
\end{pmatrix}
\]

solar

\[
\begin{pmatrix}
  \cos \theta_{13} & 0 & \sin \theta_{13} e^{-i\delta} \\
  0 & 1 & 0 \\
  -\sin \theta_{13} e^{i\delta} & 0 & \cos \theta_{13}
\end{pmatrix}
\begin{pmatrix}
  \nu_1 \\
  \nu_2 \\
  \nu_3
\end{pmatrix}
\]

SuperK, K2K, MINOS, T2K

\( \theta_{23} \approx 45^0 \)

\[ |\Delta m^2_{32}| \approx |\Delta m^2_{31}| = \]

\[ |\Delta m^2_{atm}| \approx 2.4 \times 10^{-3} \text{eV}^2 \]

T2K MINOS

\( \theta_{13} \approx 90^0 \)

Daya Bay, RENO Double Chooz

Solar experiments, SuperK KamLAND

\[ \theta_{12} \approx 34^0 \]

\[ \Delta m^2_{s1} \approx 7.5 \times 10^{-5} \text{eV}^2 \]

\[ \Delta m^2_{ij} = m_i^2 - m_j^2 \]

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

two independent \( \Delta m^2 \)
Main goals of accelerator and reactor LBL experiments

- CP violation in lepton sector

Strength of CP violation in neutrino oscillations

$$J_{CP} = \text{Im}(U_{e1}U_{\mu2} U_{e2}^* U_{\mu1}^*) = \text{Im}(U_{e2}U_{\mu3} U_{e3}^* U_{\mu2}^*)$$

$$= \cos\theta_{12}\sin\theta_{12}\cos^2\theta_{13}\sin\theta_{13}\cos\theta_{23}\sin\theta_{23}\sin\delta_{CP}$$

all mixing angles $\neq 0$ $\rightarrow$ $J_{CP} \neq 0$ if $\delta_{CP} \neq 0$

- Neutrino mass hierarchy

- $\theta_{23}$ – maximal? If not, what octant ($\theta_{23} > \pi/4$ or $\theta_{23} < \pi/4$)?

- Neutrino cross sections
- Sterile neutrinos

Quark sector $J_{CP} \approx 3 \times 10^{-5}$

Lepton sector $J_{CP} \approx 0.02 \times \sin\delta_{CP}$

First indication from T2K: $\delta_{CP} = -\pi/2$ ??
CERN Neutrino Platform

Following [2013 European Strategy for Particle Physics](http://home.web.cern.ch/) recommendations

**Initial Mandate**

...assist various groups in their R&D phase (detectors and components)....

...bring R&D at the level of technology demonstrators....

... support the long and short baseline activities (infrastructure & detectors)
Current experiments
LONG-BASELINE NEUTRINO OSCILLATION EXPERIMENT

about 500 members
59 institutions
from 11 countries

JAPAN

Tokai

Super-K

Tokyo

Kamioka Mine

Toyama

Tokyo/Narita Airport

JPARC
T2K experiment

Far neutrino detector
SuperKamiokande

Off-axis neutrino beam
Neutrino monitor INGRID
ND280
Off-axis near neutrino detector
T2K near detector ND280

280 meters from pion production target

- Tracker: 2 FGD + 3 TPC
- POD, ECAL
- SMRD

Measurement of unoscillated $\nu$ beam

- 16 identical modules (14 in cross)
- Iron/scintillator layers
- Monitor $\nu$ beam direction, profile, rate

T2K Systematics ($\nu$ mode) w/o ND280 with ND280

Appearance 11.9% 5.4%
Disappearance 12.0% 5.0%

2-3%
WAGASCI + Baby-MIND

WAGASCI detector

Neutrino cross sections – the main source of systematic uncertainties

ND280 → CH neutrino target
SuperKamiokande → H₂O neutrino target

active target filled with H₂O and scintillator 80%:20% (H₂O:CH)
**Baby-MIND**

Neutrino magnetized detector Baby-MIND - NP05 project in framework of CERN Neutrino Platform

Baby-MIND has 18 active modules
Active elements – scintillator detectors with WLS/SiPM readout
Each module: 95 horizontal bars and 16 vertical bars
Horizontal bar: 2900(L)x30(W)x7(t) mm³
Vertical bar: 1950(L)x210(W)x7(t) mm³
In total ~1800 horiz and 250 vert sci bars and 3-cm thick 33 magnetized iron plates

A spectrometer to measure muon momentum and charge identification.

**Scintillator plane**  **Two half-modules**  **Complete module**  **Magnetized iron plate**

Reconstruction efficiency > 95%
Charge identification > 90%
Start data taking with WAGASCI target in Autumn 2017

B = 1.5 T
Upgrade of T2K near detectors

For T2K-II phase and HyperKamiokande

T2K systematic errors of \( \sim 5-6\% \)
Need to improve to \( \leq 3\% \)

Current ND280

Concept for Upgrade

- new tracking target
- new TPS for high angle tracks

Plan: TDR -2017, Commissioning -2020

Intermediate (\( \sim 1 \) km)
Water Cherenkov detector NuPRISM
Span several off-axis angles

NuPRISM: arXiv:1412.3086
NOVA

Neutrino beam from FNAL to Ash River
Baseline 810 km
Neutrino beam 14 mrad off-axis
Far detector: 14 kt fine-grained calorimeter
65% active mass
Near Detector: 0.3 kt fine-grained calorimeter

Taking data since Summer 2014
Study of $\nu_\mu \rightarrow \nu_\mu$ and $\nu_\mu \rightarrow \nu_e$ oscillations
Reactor experiments

Daya Bay, China

RENO, Korea

Double Chooz, France

Principle

\[ \bar{\nu}_e + p \rightarrow e^+ + n \]

30 µs \( \sim n + Gd \rightarrow Gd^* \rightarrow Gd + \gamma s \) (8 MeV)

200 µs \( \sim n + H \rightarrow D + \gamma \) (2.22 MeV)

Typical energy resolution

\[ \sigma_E \sim (6-8)\%/\sqrt{E} \]

Detector Daya Bay

- Antineutrino detector
  - 3 separated regions - GdLS, LS, MO
  - 192x 8” PMT
  - 3 ACUs with radioactive sources and LED for weekly energy calibration

Automated calibration units

- Mineral oil
  - 37 ton
- Liquid scintillator
  - 22 ton

\[ \theta_{13} = 8.4 \text{ deg} \]

Next generation: experiment JUNO

Daya Bay: nGd
RENO: nGd
Daya Bay: nH
D-CHOOZ: nGd
RENO: nH
D-CHOOZ: nH

0.02 0.04 0.06 0.08 0.1 0.12 0.14

\[ \sin^2 2\theta_{13} \]
Future LBL Projects

- Reactor experiment JUNO
- Accelerator LBL experiment DUNE
- HyperKamiokande and T2HK
Reactor experiment JUNO

China

66 institutions
> 400 collaborators

Main target:
Measurement of neutrino mass hierarchy

- 700 m deep underground
- 36 GW reactor power
- 53 km baseline -> oscillation maximum $\theta_{12}$
- 20 kton LS detector
- 3% energy resolution at 1MeV
- <1% energy scale uncertainty

Kaiping, Jiangmen city, Guangdong Province

Overburden ~ 700 m

Start data taking in 2020
**Central detector**
- Acrylic sphere+
- 20kt Liquid Scin+
- ~17000 20’’ PMT+
- ~36000 3’’ PMT

**Water Cherenkov**
- ~2000 20’’ PMT

**Top Tracker**

**Calibration**

**Detector JUNO**

**Requirements:**
- PMT coverage 75% of total surface
- QE ~ 35%
- Sci. att. length >20 m

h=44 m

d=43.5 m
20” PMT’s

Transmission and reflection photocathode:
QE (400 nm) ~ 30%

<table>
<thead>
<tr>
<th>Characteristics</th>
<th>unit</th>
<th>MCP-PMT (IHEP)</th>
<th>R12860 (Hamamatsu)</th>
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<tr>
<td>Electron Multiplier</td>
<td>--</td>
<td>MCP</td>
<td>Dynode</td>
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<td>Photocathode mode</td>
<td>--</td>
<td>reflection= transmission</td>
<td>transmission</td>
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<td>Quantum Efficiency (400 nm)</td>
<td>%</td>
<td>26 (T), 30 (T+R)</td>
<td>30(T)</td>
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<td>Relativity Detection Efficiency</td>
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<td>~100%</td>
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<td>ns</td>
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<td>~3</td>
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<td>Rise time/ Fall time</td>
<td>ns</td>
<td>R-2, F-10</td>
<td>R-7, F-17</td>
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<td>Anode Dark Count</td>
<td>Hz</td>
<td>~30K</td>
<td>~30K</td>
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<td>After Pulse Time distribution</td>
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<td>4, 17</td>
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<tr>
<td>After Pulse Rate</td>
<td>%</td>
<td>3</td>
<td>10</td>
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<tr>
<td>Glass</td>
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<td>Low-Potassium Glass</td>
<td>HARIO-32</td>
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Sen Qian, talk at NNN16
LBNF/DUNE Project

Main goals:
- discovery of CP violation in leptonic sector
- neutrino mass hierarchy at >5σ level
- neutrino astronomy
- proton decay search

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

Single and Dual phase detectors

E_p = 60-120 GeV
Beam power 1.2 -> 2.4 MW
On axis neutrino beam
E_ν ~ 1-6 GeV
L=1300 km from FNAL to SURF, S.Dakota

Sensitivity to CP violation

2021 – installation of 1st far detector
2024 – 2 modules operational
2026 – deliver neutrino beam

Flagship FNAL project

30 countries
161 institutions
~1000 collaborators

DUNE CDR
1\textsuperscript{st} 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

J. Insler, talk at LLWI2017
- Electrons extracted from LAr to gaseous volume
- Signal amplified by LEM
- Drift (vertical) 12 m
- Signal/Noise 100:1
- Photon detectors: PMTs + WLS
- Small number of channels
- No dead material inside the active volume
DUNE Near Detector

T.Kutter, talk at HINT2016

Fine Grained Tracker inside 0.4 T magnetic field: straw-tube tracker
Surrounded by lead-scintillator ECal and RPC muon tracker

Multiple nuclear targets:
Ar, C, Ca, Fe, ...

Other designs under consideration:
- Magnetized LAr TPC
- High-pressure GAr TPC
LAr detectors at CERN Neutrino Platform
NP02: WA105, DP demonstrator + ProtoDUNE DP

S. Murthy, talk at TPC-2016

Demonstrator: 3x1x1 m$^3$ – 5 tons

ProtoDUNE DP: 6x6x6 m$^3$
300 tons active mass

Measurements with test beam in 2018

Cosmic data taking gas begun
LAr detectors at CERN Neutrino Platform

NP04: ProtoDUNE SP

400 tons active mass

Tests:
- Full size of APAs, CPAs
- Drift regions
- >15000 TPC channels
- Photon detectors
HyperKamiokande

Japan

HyperK: 2 water tanks

12 countries
70 institutes
~300 members
Expected data taking start 2026

1 tank
60 m(H)x74m(D)
Total volume 260 kt
Fiducial volume 190 kt
~10xSuperK
PMT coverage 40%
40000 PMTs

10 years of running:
- 8σ for δCP = - π/2
- 80% coverage of δCP parameter space with >3σ
p → π0 e+ >10^{35} y

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

- Upgrade of JPARC to 1.3 MW beam power
- New/upgrade of near neutrino detectors

Upgrade of JPARC to 1.3 MW beam power
New/upgrade of near neutrino detectors
PMTs for HyperKamiokande

50 cm Box&Line PMT
R12860-HQE (Box&Line dynode)

50 cm Hybrid Photo-Detector (HPD)
R12850-HQE (Avalanche diode)

Developed
→ Photo-detector
in Hyper-K baseline design

Under development
→ Possible further improvement of Hyper-K

Implosion tests
at 60 and 80 m depth
No chain implosion observed

Performance of new photosensors

High Quantum Efficiency (QE)

Super-K 22% at peak
Box&Line PMTs 30%
HPD 36%

Single Photoelectron (PE) Charge

[σ / peak]
Super-K 53%
Box&Line 35%
HPD 15%

Transit time at single pe

Super-K PMT 7.3 ns
Box&Line PMT 4.1 ns
HPD 3.6 ns

Multi-PMT option
KM3NeT module
**Conclusion**

Very intense R&D for neutrino detectors

**Current experiments:** detector upgrades to reduce systematics
- active neutrino targets
- Cherenkov detectors
- magnetized detectors

Main goals of new projects: CP violation, MH oscillation parameters, proton decay

**Next generation detectors**
- **Reactor experiment JUNO** under construction
- **Accelerator experiment DUNE** approved
- **HyperKamiokande and T2HK** approval in progress
Thank you!