Neutrino Physics and Detectors

Liangjian Wen

International Conference on Technology and Instrumentation in Particle Physics (TIPP), Beijing, May 21-26, 2017
What we have learned?

Standard Parametrization of the PMNS Matrix

\[ V = \begin{pmatrix}
1 & 0 & 0 \\
0 & c_{23} & s_{23} \\
0 & -s_{23} & c_{23}
\end{pmatrix}
\begin{pmatrix}
c_{13} & 0 & s_{13}e^{-i\delta} \\
0 & 1 & 0 \\
-s_{13}e^{i\delta} & 0 & c_{13}
\end{pmatrix}
\begin{pmatrix}
c_{12} & s_{12} & 0 \\
-s_{12} & c_{12} & 0 \\
0 & 0 & 1
\end{pmatrix}
\begin{pmatrix}
e^{i\rho} & 0 & 0 \\
0 & e^{i\sigma} & 0 \\
0 & 0 & 1
\end{pmatrix} \]

\[ \theta_{23} \sim 45^\circ \]

\[ |\Delta m_{32}^2| \sim 2.5 \times 10^{-3} \text{ eV}^2 \]

\[ \theta_{13} \sim 9^\circ \]

\[ \delta \sim ? \]

\[ \theta_{12} \sim 34^\circ \]

\[ |\Delta m_{21}^2| \sim 8 \times 10^{-5} \text{ eV}^2 \]

Atmospheric, LBL accelerator

Reactor, LBL accelerator

Solar, KamLAND

Quarks vs. Leptons: A big puzzle of fermion flavor mixings

CKM

\[ |U| = \begin{pmatrix}
\text{[Diagram]} \\
\text{Hierarchy!}
\end{pmatrix} \]

PMNS

\[ |V| = \begin{pmatrix}
\text{[Diagram]} \\
\text{Approximate \( \mu-\tau \) symmetry?}
\end{pmatrix} \]

\text{ CKM PMNS Hierarchy! Approximate } \mu-\tau \text{ symmetry?}
Future Neutrino Puzzles

\[ \Delta m^2_{31} > 0 \, ? \]
\[ \delta_{CP} \, ? \]
\[ \nu = \bar{\nu} \, ? \]

\[ U_{PMNS} U^+_{PMNS} = I \, ? \]
\[ \nu_s \text{ exists} \, ? \]

...
Selected Topics

• Neutrino oscillations (running & future)
  – Reactor neutrinos: Daya Bay, Double Chooz, RENO, JUNO, RENO-50, ...
  – Accelerator neutrinos: T2K, NoVA, LBNF/DUNE
  – Atmospheric neutrinos: ORCA, Hyper-K, PINGU, INO, ...
  – Solar neutrinos: SuperK, SNO, Borexino, ...
  – Sterile neutrinos

• NLDBD searches
  – KamLAND-Zen, EXO, Gerda, Majorana, CUORE/CUPID, SNO+, NEXT,
    SuperNEMO, PandaX-III, AMoRE, CANDLES, COBRA, ...

• Neutrino astronomy
  – Supernova → in combination with solar/atmospheric/reactor neutrino detectors
  – Geo-neutrinos → in combination with solar/reactor neutrinos
  – High energy neutrinos (not covered in this talk)

Precision Measurements

\[ \Delta m_{31} > 0? \]

\[ \delta_{CP} = ? \]

\[ \nu = \bar{\nu} ? \]

Apologies for incompleteness, bias and mis-handling
Reactor Experiments

- **Daya Bay**
  - $\Delta(\sin^22\theta_{13}) \sim 0.003 \rightarrow \sim 3\%$
  - $\Delta(\Delta m^2_{ee}) \sim 0.07 \rightarrow \sim 3\%$
  - operation till 2020
- **RENO**: ~5%.
  - operation funding secured until Feb. 2019
- **Double Chooz**: ~10%
  - secured to Jan. 2018 (may change)

by J. Zhao
Sterile v exists?

Parameter space allowed by LSND and MiniBooNE is excluded by the combination of MINOS(+), Daya Bay and Bugey-3

Next generation sterile experiments are almost ready (SOX, PROSPECT, SoLid, Chandler, NEOS, Neurino4, DANSS, nuLat, ...)

\[ \sin^2 2\theta_{\mu e} = 4 |U_{e4}|^2 |U_{\mu 4}|^2 \]
Accelerator Experiments

First generation LBL experiments ended

MINOS

T2K

Super-Kamiokande (ICRR, Univ. Tokyo)

NuMI beam and NOvA Near detector
Fermilab

NOvA Far Detector (on surface)
Ash River, MN
810 km
14 mrad

14 mrad (NOvA)

NOvA Simulation

14 mrad

J-PARC Main Ring
(KEK-JAEA, Tokai)

295 km

OPERA

Fermilab

Fermilab

Lake Michigan

Lake Superior
**Hits on \( \delta_{CP} \)**

---

**T2K Only**

- \( \delta_{CP} \) (radians)
- \( \sin^2 \theta_{13} \)

**T2K+Reactor**

- \( \delta_{CP} \) (radians)
- \( \sin^2 \theta_{13} \)

---

**Iwamoto, ICHEP 16**

**T2K Results**
- T2K-only consistent reactor data
- maximal mixing \( \theta_{23} = 45^\circ \) favored
- maximal CP phase \( \delta = -90^\circ \) favored

**NOvA Results**
- maximal mixing \( \theta_{23} = 45^\circ \) excluded @ 2.5\( \sigma \)
- NH, \( \delta \sim -90^\circ \) and \( \theta_{23} \sim 39^\circ \) favored
- IH and \( \delta \sim 90^\circ \) for \( \theta_{23} < 45^\circ \) excluded @ 3\( \sigma \)

---

Bian, ICHEP 16
Future Neutrino Detectors for neutrino mass ordering and $\delta_{CP}$

( protoDUNE, MicroBooNE, ICARUS-T600, SBND )
**NMO determination at JUNO**

- **Physics**
  - NMO determination: 3-4σ in 2026
  - Precision measurement of 3/6 mixing parameters
  - Rich physics: supernova-ν, geo-ν, atmospheric-ν, solar-ν, exotics, etc

- **Key:** get max. photons in a 20 kton LS detector
  - High QE PMT, high coverage
  - High transparent LS (> 20m A.L @430nm)
  - Low radioactivity (< 10^{-15} g/g (U, Th))


**reactor ν expts.**
Central detector

Water Cherenkov

Top Tracker

Calibration

Pool Depth: 44m

Pool ID: 43.5m

AS: ID 35.4m

SSLS: ID 40.1m

Acrylic sphere

(20Kt LS in it)

~18000 20” PMT

+~25000 3” PMT

~2000 20” PMT

Acrylic sphere:

ID: 35.4m

Thickness: 120mm

Water pool:

ID: 43.5m

Height: 44m

Water Depth: 43.5m

Filling + Overflow

Electronics

JUNO Detectors

AS: Acrylic sphere;  SSLS: stainless steel latticed shell
Success: 20” MCP-PMT

- **Advantages:**
  - Higher QE: transmissive photocathode at top + reflective photocathode at bottom
  - High CE: less shadowing effect
  - Easy for production: less manual operation and steps

**Project Team**

**MCP Principle**

**Design**
- 5”(8”) Prototype: 2009
- 20” Prototype: 2010~2013
- Production: 2013~2015
- Production: 2016~2019
MCP-PMT Performance

**QE & uniformity**

Min: 24.5%; Max: 29%
Average: 26.5%

**Dark rate**

**After pulse**
## PMT Purchasing of JUNO

### Characteristics

<table>
<thead>
<tr>
<th>Characteristics</th>
<th>Unit</th>
<th>MCP-PMT (NNVC)</th>
<th>R12860 (Hamamatsu)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Detection Efficiency</td>
<td>%</td>
<td>27%, &gt;24%</td>
<td>27%, &gt;24%</td>
</tr>
<tr>
<td>(QE<em>CE</em>area)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>P/V of SPE</td>
<td></td>
<td>3.5, &gt; 2.8</td>
<td>3, &gt; 2.5</td>
</tr>
<tr>
<td>TTS on the top point</td>
<td>ns</td>
<td>~12, &lt; 15</td>
<td>2.7, &lt; 3.5</td>
</tr>
<tr>
<td>Rise time/ Fall time</td>
<td>ns</td>
<td>R<del>2, F</del>12</td>
<td>R<del>5, F</del>9</td>
</tr>
<tr>
<td>Anode Dark Count</td>
<td>Hz</td>
<td>20K, &lt; 30K</td>
<td>10K, &lt; 50K</td>
</tr>
<tr>
<td>After Pulse Rate</td>
<td>%</td>
<td>1, &lt; 2</td>
<td>10, &lt; 15</td>
</tr>
</tbody>
</table>

By Scaling PMT Spec for LS quantity to reach 3σ@ 6year ➔

Decision based on risk, price, performance merit for physics

Dec. 16, 2015

15k MCP-PMT (75%) from NNVT
5k Dynode (25%) from Hamamatsu
Challenge: LS Purification

- Extremely clean LS in Borexino, relatively mature technology
- Technologies
  - $\text{Al}_2\text{O}_3$ column, distillation, gas striping, water extraction

$^{14}\text{C}/^{12}\text{C} \sim 2.7 \times 10^{-18}$

$^{238}\text{U}$ (Bi-Po 214)  
$< 9.7 \times 10^{-19} \text{ g/g (95\% CL)}$

$^{232}\text{Th}$ (Bi-Po 212)  
$< 1.2 \times 10^{-18} \text{ g/g (95\% CL)}$

$^{40}\text{K}$ no evidence (TBD)

$^{39}\text{Ar} \ll ^{85}\text{Kr}$

LS pilot plant in Daya Bay LS hall.

A new batch of purified LS was produced and filled into DYB-AD1.

→ evaluate radioactivity
→ optimize LS recipe
NMO & $\delta_{CP}$ determination via Matter Effects

Atmospheric $\nu$

Accelerator $\nu$

$\nu_\mu$ vs. $E_\nu$ [GeV]

$\nu_e$ vs. $E_\nu$ [GeV]

$\chi^2$ vs. $\delta_{CP}$

- NH
- HK
- DUNE
- T2K-II
- T2K+NOvA

$\sim2020$
Hyper Kamiokande

20x larger, same photo-coverage, better PMTs

SuperK
50 kt, PMT coverage: ~40%
Threshold: ~4 MeV
Light yield: 6 PE/MeV

• Technical issues
  – PMTs protection under pressure (60 m)
  – Water circulation system
  – High eff. PMT
ORCA

- ~5.7 Mt instrumented
- 115 strings
- 18 DOMs / string (~50 kt ~ 2 x SK)
- 31 PMTs / DOM (~3 kt ~ MINOS)
- Total: 64k*3” PMTs

Depth=2475m

Optical module
31 x 3” PMTs

\[ \nu_\mu + N \xrightarrow{cc} \text{had} + \mu \]

Track like (\(\nu_\mu\) CC)

\[ \nu + N \xrightarrow{\text{en}} \text{had} \]

Shower like (\(\nu\) NC, \(\nu_e\) CC)

\[ \nu_e + N \xrightarrow{cc} \text{had} + \text{em} \]
Indian Neutrino Observatory: INO

- 50kt magnetized Iron CALorimeter detector (ICAL) interleaved by RPC for detecting atmospheric neutrinos
  - Neutrino mass ordering
  - Octant and precision of $|\Delta m^2_{31}|$ and $\theta_{23}$
  - New physics
  - Magnetic monopole search

- Features:
  - Muons fully contained up to 20 GeV
  - Good charge resolution, B=1.5 T
  - Good tracking/Energy/time resolution

3 modules, 151 layers

One module:
16 m x 16 m x 14.5 m
EGADS and SK-Gd

Gd in water:
- GdCl$_3$ highly soluble in water
- Improve low energy detection capabilities
- Flavor sensitive
- Good for LBNE, supernova, reactor and geo-neutrinos, ...

A 200 ton-scale R&D project, EGADS – is under construction at Kamioka

\[
\bar{\nu}_e + p \rightarrow e^+ + n
\]
\[
n + p \rightarrow d + \gamma \text{ (2.2 MeV)}
\]
\[
n + \text{Gd} \rightarrow \text{Gd}^* + \gamma \text{ (8 MeV)}
\]
\[
\tau \approx 28 \mu s (0.1\% \text{ Gd})
\]
Liquid Ar TPC

- **Idea first proposed in 1985**
  - Dense target
  - Ample ionization & scintillation: good energy resolution & Low threshold
  - Excellent tracking and PID capabilities

- **Challenges**
  - LAr purity (long-drift)
  - Readout wires or large electron multipliers
  - Cold electronics
  - Cryostat for multi-kiloton TPC
DUNE LArTPC R&D: Single-Phase

- APA/CPA assemblies
- APA’s w/ “wrapped” induction wire planes
- Scintillation detection: light guides embedded in APA’s, SiPM readout

3.6 m
DUNE LArTPC R&D: Dual-Phase

- 12m max drift (vertical), LEM readout
- S/N: ~100/1
- Scintillation via PMT’s below cathode
NLDBD experiments
0νββ Decay

- Unique feasible way to determine the Majorana nature of ν. Possible to pin down mass ordering
- Lepton number violation process
- If Majorana: a natural way to understand tiny ν masses (seesaw)
- Set constraints on 2 Majorana-type CP-violating phases

![Graph showing the relationship between 0νββ decay and mass.](image)
$0\nu\beta\beta$ Decay

Different isotopes correspond to vastly different experimental techniques
- Ultra-low external background
- Good energy resolution
- Large detector volume

\[\begin{array}{c}
48\text{Ca} \\
96\text{Zr} \\
100\text{Mo} \\
115\text{Cd} \\
124\text{Sn} \\
130\text{Te} \\
136\text{Xe} \\
110\text{Pd} \\
76\text{Ge}
\end{array}\]
CUPID (Zn$^{82}$Se, Li$_2^{100}$MoO$_4$, TeO$_2$), AMoRE ($^{100}$Mo), CANDLES ($^{48}$Ca), ZICOS ($^{96}$Zr), AXEL ($^{136}$Xe), DCBA ($^{100}$Mo/ $^{150}$Nd), COBRA (CdZnTe), ...
For a none background-free experiment, the sensitivity (1st order) of $0\nu\beta\beta$ decay half-life.

\[ T^{0\nu\beta\beta}_{1/2} = \frac{\ln 2 \cdot N_A}{M_{\text{isotope}}} \cdot \frac{Mt \cdot \epsilon \cdot \eta}{\alpha \cdot \sqrt{b}} \]

* For 90% C.L, $\alpha=1.64$

- Detector Exposure
- Detector efficiency
- Isotope abundance
- Background in ROI

**Graphical Representation:**
- Data points for various experiments such as CUORE-0, GERDA (phase-II, coaxial), GERDA (phase-II, BEGe), KamLAND-Zen (phase-II, period1), KamLAND-Zen (phase-II, period2), EXO-200, nEXO (w/o Ba-tagging), JUNO Xe-LS (5 tons), and JUNO Xe-LS (50 tons).

**Background Index:**
- Background index in ROI/(10^{-3} cnts/keV/mol/yr)
Fundamental Requirements

• Enrichment of the source material
  – 10 kg/100 kg scale $\rightarrow$ ton scale

• Deep underground location to shield cosmogenic backgrounds

Several underground labs around the world, next round of experiments 1-2 km deep.
Fundamental Requirements

- Ultra-low radioactive contamination during detector construction

  Materials used $\approx 10^{-15}$ in U, Th
  (U, Th in the earth crust $\sim$ ppm)

- New Techniques to discrimination signal from background

  Non trivial for $E \sim 1$ MeV
  This gets easier in larger detectors
new collaboration formed in October 2016, members of GERDA, Majorana and other groups

**LEGEND** = Large Enriched Germanium Experiment for Neutrinoless $\beta\beta$ Decay

(up to) 200 kg in existing infrastructure at LNGS starting ~2020, background reduced by ~5 relative to GERDA

1000 kg if Ge is chosen in US down-select process, background reduced by ~30 relative to GERDA

*B. Schwingenheuer @ CERN EP seminar, Jan 2017*
Future Concepts

EXO-200

A 5000 kg enriched LXe TPC, directly extrapolated from EXO-200

EXO-200 data
M. Marino @ Neutrino2014

~ 150 kg

nEXO

130cm

~ 5000 kg

~ EXO-200 size

~ nEXO size

Bgd in total Fid Vol (Nature 2014)

40% Fid Vol

Bgd cts / (kg $^{136}_{\text{Xe}}$/ yr / (FWHM ROI))

Standoff cut (mm)
Future Concepts

Running “KamLAND-Zen 800” →
Future “KamLAND2-Zen” with 1000 kg enriched Xe.
Assumptions:

winston cones: x 1.8
Higher Q.E. PMTs: x 1.9
LAB-based liquid scint.: x 1.4
Overall: x 4.8

Expected resolution (2.6 MeV): 4% → ~2%
Target sensitivity 20 meV

Beyond JUNO: possible < 10 meV
Summary

• Few significant advances of neutrino physics. Hints on $\delta_{CP}$
• Many technological progresses $\rightarrow$ preparation for the next generation experiments
  – larger mass $\rightarrow$ 10~20 times in general, comparing to the previous generation
  – better resolution, precision, S/N ratio, etc
• New discoveries ahead of us, probably in 10 - 20 yrs
  – Neutrino mass ordering
  – Neutrino is Majorana?
  – $\delta_{CP}$
Thanks

Acknowledgements
Many Information from relevant talks given at Neutrino2016, ICHEP2016, NeuTel2017, NNN16, DBD16, etc.