NEUTRINO OSCILLATIONS
– CURRENT STATUS AND FUTURE PROSPECTS –

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Updated Contents

- Introduction
- Current status and prospect of three-generation mixing measurements
- Current status and prospect of non-three-generation mixing
- Summary
Constituents of This World

How can we distinguish btw.

\begin{itemize}
  \item $u$, $c$ and $t$
  \item $d$, $s$ and $b$
  \item $\nu_e$, $\nu_\mu$ and $\nu_\tau$
  \item $e$, $\mu$ and $\tau$
\end{itemize}

Same spin, same charge…

**Only by mass!**

Except for $\nu$’s.

+ $\alpha$ (Higgs, dark matter, dark energy…..?)
How can we distinguish neutrinos?
- It is two sides of coins-

Neutrinos do interact with matter and

- An electron neutrino changes to an electron.
- A muon neutrino changes to a muon.
- A tau neutrino changes to a tau.

And it was believed that electron neutrino only changes to electron, never into muon nor tau before the neutrino oscillation was found.
Flavor and Mass

There are three types of charged lepton \((e, \mu, \tau)\), distinguishable only via mass.

Then, three types of neutrinos, distinguishable via interaction w/ matter.

**IF NEUTRINOS HAVE MASSES, there is no need for three types to be mass eigenstates.**

\[ |\nu_e\rangle = a|\nu_1\rangle + b|\nu_2\rangle + c|\nu_3\rangle, \quad \nu_1, \nu_2, \nu_3 : \text{mass eigenstates} \]

Same thing is happening for quarks.

Partner of \(|up\rangle\) quark = \(a|down\rangle + b|strange\rangle + c|bottom\rangle\)
Then, a neutrino produced as an eigenstate of one flavor propagates with different speeds

\[ |\nu_\alpha> = |\nu_1> \cos\theta + |\nu_2> \sin\theta, \quad \alpha = e, \mu, \tau \]

\[ |\nu_1 > e^{-i \frac{m_1^2}{2E} \cos \theta} + |\nu_2 > e^{-i \frac{m_2^2}{2E} \sin \theta} \quad \Rightarrow \quad |\nu_\beta > \]

Neutrino Oscillation!

P(\nu_\alpha \rightarrow \nu_\beta) = \left| \langle \nu_\beta | \nu_\alpha \rangle \right|^2 = \sin^2 2\theta \sin^2 \left( \frac{\Delta m^2 L}{4E} \right)
Neutrinos DO interact, but ….

Mean Free path of particles

- ~1GeV neutrino (atmospheric, accelerator)
- ~1MeV neutrino (solar, reactor)
- Photons
- X-rays

Concrete Wall

- High Energy $\gamma$ ~1cm
- High Energy proton ~10cm
- ~1GeV muon ~30cm
- ~$10^8$ km $\equiv$ distance btw. Solar and earth
- ~$10^{14}$ km $\equiv$ 100 light-year
Super-Kamiokande
Super-Kamiokande

- Since April 1996
- Water Cherenkov detector w/ fiducial volume 22.5kton
- Detector performance is well-matched at sub GeV
- Excellent performance for single particle event
- Good e-like(shower ring) / $\mu$-like separation

$\sim$11000 x 20inch PMTs (inner detector, ID)
Super-Kamiokande

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Mixing angles and mass\(^2\) differences have been measured by various neutrino sources.

\[
\left( \begin{array}{c} \nu_e \\ \nu_\mu \\ \nu_\tau \end{array} \right) = U_{PMNS} \left( \begin{array}{c} m_1 \\ m_2 \\ m_3 \end{array} \right)
\]

\[
U_{PMNS} = \begin{pmatrix}
1 & 0 & 0 \\
0 & c_{23} + s_{23} & 0 \\
0 & -s_{23} + c_{23} & 0
\end{pmatrix}
\]

\[
(c_{ij} = \cos \theta_{ij}, s_{ij} = \sin \theta_{ij})
\]

\[
\begin{pmatrix}
\begin{pmatrix}
+ c_{13} & 0 & + s_{13} e^{-i\delta}
\end{pmatrix} \\
0 & 1 & 0 \\
\begin{pmatrix}
- s_{13} e^{i\delta} & 0 & + c_{13}
\end{pmatrix}
\end{pmatrix}
\]

\[
\begin{pmatrix}
+ c_{12} & + s_{12} & 0 \\
- s_{12} & + c_{12} & 0 \\
0 & 0 & 1
\end{pmatrix}
\]

- \(\theta_{23}, |\Delta m^2_{32}|\), mass order
- \(\theta_{13}, |\Delta m^2_{32}|\)
- \(\theta_{13}, \delta_{CP}\)
- \(\theta_{12}, \Delta m^2_{21}\)

\[
\frac{L}{E} \sim 0.5 \text{ km/MeV}
\]

\[
\frac{L}{E} \sim 15 \text{ km/MeV}
\]

- Atmospheric \(\nu_\mu/\bar{\nu}_\mu/\nu_e/\bar{\nu}_e\)
- Accelerator \(\nu_\mu/\bar{\nu}_\mu\)
- Reactor \(\bar{\nu}_e\)
- Solar \(\nu_e\)
What we know about neutrino mass

- $\Delta m_{21}^2 \equiv m_2^2 - m_1^2 = 7.53 \times 10^{-5} \text{ eV}^2$
- $\Delta m_{32}^2 \equiv m_3^2 - m_2^2 = 2.51 \times 10^{-3} \text{ eV}^2 \text{ or } -2.56 \times 10^{-3} \text{ eV}^2$
- Cosmological observations
  \[ \sum_j m_j < 0.12 \text{ eV} \text{ (95\% CL)} \]
  \[
  \downarrow
  \]
- If $m_1 \ll m_2 \ll m_3$, $m_2 \sim 9 \text{ meV}$, $m_3 \sim 50 \text{ meV}$

![Graph showing mass hierarchy and cosmological observations](image)
Mixing btw. Flavor and Mass

quark mixing matrix (CKM)
\[
\begin{pmatrix}
0.9742 & 0.2243 & 0.0039 \\
0.218 & 0.997 & 0.042 \\
0.0081 & 0.04 & 1.02
\end{pmatrix}
\]

lepton mixing matrix (PMNS)
\[
\begin{pmatrix}
0.82 & 0.55 & 0.146 \\
-0.469 & 0.51 & 0.71 \\
0.32 & -0.66 & 0.70
\end{pmatrix}
\]

* smallest digits correspond to the current precision
Accelerator-based Long Baseline Neutrino Experiment

Neutrino beamline

Proton Accelerator

Decay Volume

Beam dump

Target & Horns

Near Detector

Far Detector

A few 100m ~ a few km

A few 100km

timing synchronized using GPS

Toroidal magnetic field by ‘horn’ focuses

\( \pi^+ \rightarrow \nu_\mu \) beam

or

\( \pi^- \rightarrow \bar{\nu}_\mu \) beam
Oscillations peculiar to the long baseline experiment

\[ \nu_\mu \text{ disappearance } \sim \alpha \sin^2 \theta_{23} \sim 100\% \text{ at right energy} \]

\[ \nu_e \sim \alpha \sin^2 \theta_{23} \sin^2 \theta_{13} \sim 5\% \]

\[ \nu_\tau \sim \alpha \cos^4 \theta_{13} \sin^2 \theta_{23} \sim 95\% \]

A.K. Ichikawa
Neutrino oscillation among three states

$$U_{\text{PMNS}} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & +c_{23} & +s_{23} \\ 0 & -s_{23} & +c_{23} \end{pmatrix} \begin{pmatrix} +c_{13} & 0 & +s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & +c_{13} \end{pmatrix} \begin{pmatrix} +c_{12} & +s_{12} & 0 \\ -s_{12} & +c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

$$c_{ij} = \cos \theta_{ij}, s_{ij} = \sin \theta_{ij}$$

Two neutrinos case

Three neutrinos case

Depending on the value of $\delta_{CP}$, neutrino and antineutrino oscillate differently.
CV violation!
Oscillations peculiar to the long baseline experiment

Since $\theta_{12}, \theta_{13}, \theta_{23}$ are known from other measurements, $\delta_{CP}$ can be determined $\nu_\mu \to \nu_e$ measurement, even w/o $\bar{\nu}_\mu \to \bar{\nu}_e$ meas.

CP violation is accessible only via appearance.

$\nu_\mu$ disappearance $\sim \propto \sin^2 \theta_{23} \sim 100\%$ at right energy

$\nu_e 
\sim \propto \sin^2 \theta_{23} \sin^2 \theta_{13} \sim 5\%$

$\nu_\tau 
\sim \propto \cos^4 \theta_{13} \sin^2 \theta_{23} \sim 95\%$

$\bar{\nu}_e$

Interference term
$\sim \propto \sin \delta_{CP}$ for neutrino
$\sim \propto -\sin \delta_{CP}$ for antineutrino
$\pm 27\%$ effect on $\nu_e$ appearance
Some complexity from matter effect
“Earth is not symmetric about flavor nor CP”

• Neutrino feels potential from matter → affect oscillation
  • Difference between $\nu_e$ and $\nu_\mu/\nu_\tau$
    • No muon nor tau inside Earth
  • Difference between $\nu$ and anti-$\nu$
    • No antimatter inside Earth
    • oscillation prob. is different for $\nu_\mu \rightarrow \nu_e$ and $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$!

• Matter effect is larger for higher-$E$ or Longer $L$
• Effect is opposite depending on mass order
  • normal($m_1 < m_2 < m_3$) vs inverted($m_3 < m_1 < m_2$)
Running Accelerator long baseline experiments T2K and NOvA

Matter effect \(\sim 10\%\) for T2K and \(\sim 30\%\) for NOvA Important to resolve degeneracies)
Running Accelerator long baseline experiments T2K and NOvA

T2K
- 181 MeV LINAC
- 3 GeV RCS
- T2K Neutrino Beamline
- 30 GeV Main Ring

NOvA
- 120 GeV

Accumulated POT

Beam Power (kW)

Weekly neutrino beam
Weekly antineutrino beam
Accumulated beam
Accumulated neutrino beam
Accumulated antineutrino beam

$\sim 500\text{kW}$

$\sim 720\text{kW}$
Running Accelerator long baseline experiments
T2K and NOvA

T2K

Super-Kamiokande
50 kt Water Cherenkov detector

NOvA

14kt segmented liquid scintillator
Results in June 2018

$\nu_e$ (CCQE)  

$\nu_e$ (w/ $\pi^+$)  

$\bar{\nu}_e$  

T2K

NOvA Preliminary
Results in June 2018

T2K: more $\nu$, less anti-$\nu$ than expected $\rightarrow$ large CP violation?
NOvA: less $\nu$, more anti-$\nu$ than T2K best fit point...
Hint of CP violation by T2K

T2K CP conserving case ($\delta_{CP} = 0, \pi$) is disfavored by >2\sigma (95\%) C.L.
T2K and NOvA other results

NOvA Preliminary

T2K posterior probability for mass ordering:
Normal 89%, Inverted 11%
T2K neutrino and antineutrino disappearance result in 2017

Disappearance

- Should match with neutrino measurement. If different, violation of the CPT theorem or unknown non-standard neutrino-matter interaction

- If CPT is violated as \( \frac{m^2}{\Lambda_{NP}} \), effect can be comparable to \( \Delta m^2 \) even if \( \Lambda_{NP} \) is as high as \( 10^{14} \) GeV

- Consistent with neutrino measurement.
T2K and NOvA future prospects

• Both experiments are proposing extensions.

T2K CPV sensitivity

Δχ² to exclude sin²δₐ = 0

Protons-on-Target (x10²¹)

2026

T2K sensitivity to CPV

Mass order unknown

Mass order known

NOvA

NOvA Simulation

Normal δCP=3π/2, sin²θ23=0.403
Δm²=2.5×10⁻³eV², sin²θ13=0.022

NOvA joint νe+νμ

Max. mixing

Hierarchy

Octant

CPV

2016 analysis techniques with projected systematic uncertainty improvements

2016
BTW, SK-Gd
-dissolve Gd to SK water for neutron tagging -

- 0.2% loading of $\text{Gd}_2(\text{SO}_4)_3$
- Signal = $\bar{\nu}_e + p \rightarrow e^+ + n$
- Reduce background by neutrino tagging with Gadolinium
- SK tank was opened in June 2018 for the first time in 12 years.
- 0.02% loading will happen in JFY2019
Supernova Relic Neutrino

Next generation Accelerator long baseline experiments
Hyper-Kamiokande and DUNE

Both experiments are aiming to start around 2026.
Matter effect \( \sim 10\% \) for T2HK and \( \sim 45\% \) for DUNE
Next generation Accelerator long baseline experiments
Hyper-Kamiokande and DUNE

Hyper-K
J-PARC

Hyper-K

Hyper-K
text

Hyper-K

Hyper-K
text

DUNE

120 GeV

DUNE

DUNE

current (≈500 kW) 
→ 1.3 MW by upgrading RF etc.

current (≈700 kW) 
→ 1.2 MW by upgrading LINAC etc.
Next generation Accelerator long baseline experiments
Hyper-Kamiokande and DUNE

Multipurpose
• Acc. long baseline neutrino oscillation
• atmospheric neutrino
• Solar neutrino
• Supernovae neutrino
• proton decay
etc.
Next generation Accelerator long baseline experiments Hyper-Kamiokande and DUNE

Hyper-K

\[
sin^2\delta_{CP} = 0 \text{ exclusion}
\]

Normal mass hierarchy
\[sin^2\theta_{13} = 0.1, \quad sin^2\theta_{23} = 0.5\]

HK 1 tank 10 years

DUNE

CP Violation

DUNE Sensitivity
Normal Ordering
\[sin^2\theta_{13} = 0.085 \pm 0.003\]
\[\theta_{23}: \text{NuFit 2016 (90\% C.L. range)} \quad \text{---} \quad sin^2\theta_{23} = 0.441 \pm 0.042\]

\[
\sigma = \sqrt{\chi^2}
\]

Width of band indicates variation in possible central values of \(\theta_{23}\)
Prospect of mixing angle determination
High precision and redundant measurements

* may not be precise comparison

Ploted $\sin^2 \theta$ to see the size of mixing
Prospect of $\Delta m^2$ determination
High precision and redundant measurements

* may not be precise comparison

PDG18

KamLAND

MINOS

T2K

NOvA

Daya Bay

T2K-II $\sim$2025?

JUNO $\sim$2027?

DUNE $\sim$2030?

HK

similar for NOvA?

<1%

~2025?

0.4%

~2027?

~2027?
Mass Ordering

• normal (1st gen. < 2nd gen < 3rd gen) or inverted (3rd gen < 1st gen < 2nd gen)?
  • Important to understand how masses are assigned to elementary fermions

• Big impact to neutrinoless double-beta decay search
  ✓ normal ordering → lighter $m_{\beta\beta}$
  ✓ Detector necessary ~1 ton vs $\geq 10$ ton

• two ways proposed
A) Matter effect in Earth for (anti-) $\nu_\mu \leftrightarrow$ (anti)$\nu_e$
B) Amplitude difference for two frequencies
Mass Ordering

A) Matter effect in Earth for \((\text{anti-})\nu_\mu \leftrightarrow (\text{anti})\nu_e\)

\[
H = U_{PMNS} \begin{pmatrix} 0 & 0 & 0 \\ 0 & \frac{\Delta m^2_{21}}{2E} & 0 \\ 0 & 0 & \frac{\Delta m^2_{31}}{2E} \end{pmatrix} U^*_{PMNS} + \begin{pmatrix} \pm \frac{2\sqrt{2}G_F n_e E}{2E} & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \end{pmatrix}
\]

Especially, resonance happens at \(E = \frac{\Delta m^2 \cos 2\theta}{2\sqrt{2}G_F n_e}\)

Effect of Earth matter has \textit{not yet observed} due to relatively small \(\sin^2 2\theta_{13}\)

Normal Mass ordering

Inverted Mass Ordering
Atmospheric neutrino by Super-K

Super-Kamiokande Collaboration, 
Phys. Rev. D 97, 072001

the inverted mass hierarchy is disfavored by between 81.9% and 96.7% for SK by itself and by between 91.9% and 94.5% when SK is combined with T2K for the $\theta_{13}$-constrained fits.
Other Atmospheric Neutrino Mass Order measurements in (near) future

- PMT arrays in Atlantic Ice
- Red points are PINGU 26 strings
- Low energy branch of KM3NeT in Mediterranean Sea

IceCube Laboratory
Data is collected here and sent by satellite to the data warehouse at UW–Madison

Digital Optical Module (DOM)
5,160 DOMs deployed in the ice

IceCube detector

Amundsen–Scott South Pole Station, Antarctica
A National Science Foundation–managed research facility

2450m Depth
The ORCA Detector
- 6 Mton instrumented
- 115 strings
- 18 DOMs / str
- 31 PMTs / DOM
- Total: 64K 3” PMTs

Low energy branch of KM3NeT in Mediterranean Sea
Mass Ordering

B) Amplitude difference for two frequencies

\[ P(\bar{\nu}_e \rightarrow \bar{\nu}_e) = (\text{leading term}) \]

\[ -\sin^22\theta_{13} \left( \cos^2\theta_{12} \sin^2 \Delta m^2_{31} \frac{L}{4E} + \sin^2\theta_{12} \sin^2 \Delta m^2_{32} \frac{L}{4E} \right) \]

\[ 0.69 \]

\[ 0.31 \]

Vacuum oscillation probability \( P(\nu \rightarrow \nu) \)

Here for \( \Delta m^2_{31} + \Delta m^2_{32} = 2 \times 2.49 \times 10^{-3} \text{eV}^2 \)

\( \Delta m^2_{31} \) for NO

\( \Delta m^2_{32} \) for IO

\(~50-60 \text{ km for energies of reactor } \nu\)
JUNO

2016:
- Start PMT testing
- TT arrived

2017:
- Start PMT testing
- TT arrived

2018:
- PMT potting starts
- Delivery of surface buildings
- Start production of acrylic sphere

2019-2020:
- Electronics production starts
- Civil work and lab preparation completed
- Detector constructing

2021:
- Detector ready
- Data taking!

Y. Cheng, NuPhys2018

Central detector
Acrylic sphere +
20kt Liquid Scin +
18,000 20" PMTs
~25000 3" small PMTs

Water Cherenkov
~2400 20" PMT

AS: ID35.4m

SSLS: ID40.1m

Filling + Overflow

Calibration

Top Tracker
Prospect of Mass Ordering determination

\[ \text{if } \delta = -\pi/2 \text{ and NO (if not, NOvA+T2K)} \]

* may not be precise comparison

sensitivity

current result
Other Topics
Solar neutrino

\[ \sin^2(\theta_{12}) = 0.316 \pm 0.034 \]
\[ \Delta m^2_{21} = (7.54 \pm 0.18) \times 10^{-5} \, \text{eV}^2 \]
\[ \sin^2(\theta_{13}) = 0.0219 \pm 0.0014 \]

\[ \sin^2(\theta_{12}) = 0.308 \pm 0.014 \]
\[ \Delta m^2_{21} = (4.85 \pm 1.33) \times 10^{-5} \, \text{eV}^2 \]
\[ \sin^2(\theta_{13}) = 0.007 \pm 0.013 \]

\[ \Delta m^2_{21} = (7.40 \pm 0.18) \times 10^{-5} \, \text{eV}^2 \]

\ (~2\sigma\ tension\ between\ solar\ global\ and\ KamLAND)
LSND & MiniBooNE $\nu_\mu \rightarrow \nu_e$ anomaly

- Conflicting with three $\nu'$s
- Conflicting with IceCube, MINOS+, Daya Bay if mixing with 4th $\nu$
- Acc. short baseline experiments in FNAL and J-PARC will investigate.

LSND, 1995

MiniBooNE


Reactor `anomaly'

\[
\bar{y}_f = (5.785 \pm 0.113) \times 10^{-43} \text{ cm}^2/\text{fission}
\]

H-M model: \[
\bar{y}_f = (6.271 \pm 0.150) \times 10^{-43} \text{ cm}^2/\text{fission}
\]

I. Yu, “Recent Results from RENO” neutrino 2018
Neutrino-4

2.8σ oscillation effect

Tension with Prospect

arXiv:1809.10561
Summary

- Mixing in three generations in the lepton sector has been established by measuring neutrinos from atmospheric, Solar, reactor and accelerator.

- Remaining's are CP-violation phase and mass ordering
  - T2K $2\sigma$ confidence interval $-170^\circ < \delta_{CP} < -36^\circ$, CP conserving case ($\delta_{CP} = 0^\circ, 180^\circ$) is outside.
  - Normal mass ordering is preferred by $\gtrsim 90\%$

- Next generation experiment will fully explore CP-violation phase, mass ordering, and also start exploring beyond the three-generation mixing.
  - Hyper-Kamiokande, DUNE, JUNO etc.

- LSND/MiniBooNE anomaly will be confirmed/refuted by short baseline programs at FNAL and JSNS$^2$ at J-PARC.

- Many experiments to tackle the reactor abnormally.