Recent Long baseline Neutrino Oscillations Results

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• Brief History of Neutrinos
• Neutrino Properties and Oscillations
• How Neutrinos are Produced and Detected
• Long Baseline Neutrino Experiments
  • 2015 Nobel Prize in Physics for ν oscillation discovery
  • T2K and Nova Results
• Summary

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Selected SHORT HISTORY of Neutrinos

• 1930, Pauli proposed neutrinos to explain beta decay
• 1956, Cowan and Reines, detected neutrinos from reactors
• 1962, Schwartz et.al., Two neutrino types or flavors; $\nu_e$ and $\nu_\mu$.
• 1964, Standard Model of Leptons invented by Weinberg, Salam, and Glashow.
• 1998, Super Kamiokande finds atmospheric $\nu$ oscillations (2015 Nobel)
• 2002, SNO expt measures solar $\nu$ oscillations (2015 Nobel)
• 2013, T2K measures $\nu_\mu \rightarrow \nu_e$ appearance and reactors observe $\bar{\nu}_e \rightarrow \nu_e$ disappearance

Long Base Line Experiments

• Natural $\nu$ source, with $\nu$’s travelling over $10^4$-$10^8$ km
  • Super Kamiokande measurement of atmospheric $\nu$
  • SNO measurement of solar $\nu$’s from Sun
• Artificial $\nu$ source, $\nu$’s traveling over 100’s km.
  • K2K, from Tsukuba to Kamioka Mine
  • MINOS, from Chicago to Soudan Mine
  • Opera, from CERN to Gran Sasso Mine
  • T2K, from Tokai to Kamioka Mine
  • Nova, from Chicago to Ash River

The Nobel Prize in Physics 2015
Takaaki Kajita, Arthur B. McDonald
Unusual Neutrino Properties

• Neutrinos are neutral Spin ½ Fermions that are nearly massless particles and travel nearly at speed of light
• Neutrinos interact very weakly, $\sigma \approx 10^{-38}$ cm$^2$/E$_\nu$(GeV)
  • 1 GeV neutrino in water will travel very far $\sim 10^9$ miles (distance to Saturn) before interacting. Very weak interaction.
• Neutrinos found in nature ONLY have spin direction opposite to momentum direction ("left handed" helicity).
  • "right handed" neutrinos do not exist in nature
• Three types or flavors; $\nu_e$, $\nu_\mu$, $\nu_\tau$
  • Each type is produced or annihilated at the same time with the corresponding charged lepton, e, $\mu$, or $\tau$.
  • Ex. in decays; $\mu^- \rightarrow \nu_\mu + X$ and $\tau^- \rightarrow \nu_\tau + X$.
  • Ex. in capture; $\nu_e + N \rightarrow e^- + X$ and $\nu_\mu + N \rightarrow \mu^- + X$. 
Neutrino Flavor and Mass eigenstates

Each neutrino flavor type eigenstate, $\nu_e$, $\nu_\mu$, and $\nu_\tau$, is a linear combination of neutrino mass eigenstates, $\nu_1$, $\nu_2$, and $\nu_3$. We can write the QM plane wave function as;

$$|\nu_e\rangle = U_{e1}|\nu_1\rangle + U_{e2}|\nu_2\rangle + U_{e3}|\nu_3\rangle$$

$$|\nu_\mu\rangle = U_{\mu1}|\nu_1\rangle + U_{\mu2}|\nu_2\rangle + U_{\mu3}|\nu_3\rangle$$

$$|\nu_\tau\rangle = U_{\tau1}|\nu_1\rangle + U_{\tau2}|\nu_2\rangle + U_{\tau3}|\nu_3\rangle$$

Each neutrino mass eigenstate j has different masses $m_j$, j=1,2,3

$$|\nu_j\rangle = e^{-imjc^2t/\hbar}|\nu_j(t = 0)\rangle, \quad j = 1,2,3$$

Experimentally only know, $m_1$ & $m_2$ close, but $m_3$ far apart from others

$$|m_1^2 - m_2^2| \approx 7.6 \times 10^{-5} \text{ eV}^2 \text{ and } |m_1^2 - m_3^2| \approx 2.4 \times 10^{-3} \text{ eV}^2$$

unknown if $m_2 < m_3$ or visa versa, “mass hierarchy problem”. This talk will assume $m_2 < m_3$, normal hierarchy
The neutrino mixing between 3 flavor states and 3 mass states can be formed into a 3x3 matrix

\[
\begin{pmatrix}
|v_e\rangle \\
v_\mu \\
v_\tau\
\end{pmatrix} =
\begin{pmatrix}
U_{e1} & U_{e2} & U_{e3} \\
U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\
U_{\tau 1} & U_{\tau 2} & U_{\tau 3}
\end{pmatrix}
\begin{pmatrix}
|v_1\rangle \\
v_2 \\
v_3\
\end{pmatrix}
\]

The neutrino 3x3 mixing matrix, can be separated into 3 unitary mixing matrices.

\[
\begin{pmatrix}
U_{e1} & U_{e2} & U_{e3} \\
U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\
U_{\tau 1} & U_{\tau 2} & U_{\tau 3}
\end{pmatrix} =
\begin{pmatrix}
\cos \theta_{12} & \sin \theta_{12} & 0 \\
-\sin \theta_{12} & \cos \theta_{12} & 0 \\
0 & 0 & 1
\end{pmatrix}
\begin{pmatrix}
\cos \theta_{13} & 0 & e^{-i\delta} \sin \theta_{13} \\
0 & 1 & 0 \\
0 & -\sin \theta_{32} & \cos \theta_{32}
\end{pmatrix}
\begin{pmatrix}
1 & 0 & 0 \\
0 & \cos \theta_{32} & \sin \theta_{32} \\
0 & -\sin \theta_{32} & \cos \theta_{32}
\end{pmatrix}
\]

Due to the complex phase angle \( \delta \), the neutrino mixing introduces CP violation. This idea was predicted for Quark mixing by Kobayashi & Maskawa (2008 Nobel Prize) whose model was verified by Belle & BaBar.

Note this is very far reaching prediction, Ex. CP violation could have been introduced via exchange of a new particle (ex. Z boson leads to atomic parity violation). But for CP violation we have a very different mechanism which is mixing of flavor and mass eigenstates. To find CP violation we need to have non-zero value of \( \theta_{13} \). Recent results, the first non-zero \( \theta_{13} \) came from T2K (Summer 2011) and very precise Reactor measurements find \( \theta_{13} \approx 9 \) degrees. The search for CP violation is now the paramount next step in particles physics.
EXPERIMENTAL RESULTS on $\nu$ mixing angles and masses

$\theta_{12} \approx 34^o$, $\theta_{23} \approx 45^o$, $\theta_{13} \approx 9^o$

Expt. $M(\nu_e) < 2.2$ eV

Mass eigenstate axes; $\nu_1, \nu_2, \nu_3$
Flavor eigenstate axes; $\nu_e, \nu_\mu, \nu_\tau$

$m_{12}^2 \approx 7.6 \times 10^{-5}$, $m_{23}^2 \approx 2.4 \times 10^{-3}$ eV$^2$

It appears that $\theta_{23}$ is exactly 45 deg. Before the T2K expt, theorists thought that $\theta_{13}$ was zero, but it turned not to be zero!! The $\nu_3$ is exactly 50/50 $\nu_\tau$ and $\nu_\mu$ but $\nu_2$ is has about equal amounts of the 3 flavor neutrinos. The 3rd neutrino mass eigenstate mass is very different from the other 2.
**$\nu_e$ Appearance/$\nu_\mu$ Disappearance vs Distance (T2K)**

\[ P(\nu_\mu \rightarrow \nu_e) = \left| \langle \nu_e | \nu_\mu \rangle \right|^2 \]

\[ = \left| \sum_i U_{ei} e^{-i\Delta m_{i1}^2 x/2E} U_{\mu i}^* \right|^2 \]

**APPEARANCE**

\[ P(\nu_\mu \rightarrow \nu_e) \text{ vs. distance} \]

Maximal appearance $P=5\%$ occurs at $\sim 300$ km

Distance $x$ in kilometer that neutrino travels

Since the observed rate at $x=300$ km is $5\%$, then $P(\nu_\mu \rightarrow \nu_\tau)=95\%$

**DISAPPEARANCE**

\[ P(\nu_\mu \rightarrow \nu_\mu) = \left| \langle \nu_\mu | \nu_\mu \rangle \right|^2 \]

\[ = \left| \sum_i U_{\mu i} e^{-i\Delta m_{i1}^2 x/2E} U_{\mu i}^* \right|^2 \]

ASSUME

- $\theta_{12}=34^\circ$
- $\theta_{23}=45^\circ$
- $\theta_{13}=9^\circ$
- $(\Delta m^2)_{12}=7.6E-5$
- $(\Delta m^2)_{23}=2.4E-3$
- $\delta_{CP}=0$
- $E_\nu=0.6$ GeV

Maximal disappearance $P=0\%$ occurs at $\sim 300$ km
The neutrino starts out 100% a muon neutrino and as it travels it oscillates and the Muon flavor totally disappears into tau neutrino (95%) and electron neutrino (5%).

Then neutrino will oscillate back into a muon neutrino.

This is a graphical visualization of neutrino oscillating between flavor states.
**Neutrino Appearance Oscillation**

Neutrinos created at accelerator site \( \rightarrow \) \( \mu^- \rightarrow W^- \rightarrow v_\mu \rightarrow v_e \rightarrow e^- \rightarrow W^+ \rightarrow \) Neutrinos detected at far site

*Neutrino oscillations traveling 100’s of kilometers and new \( v_e \) flavor appears \( \Rightarrow \) sensitive to \( \theta_{13} \) & \( \delta_{CP} \)

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The Nobel Prize in Physics 2015
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The SNO detector contains heavy water and is sensitive to charged current $\nu_e$ interactions and to neutral current interactions, where $\nu_{e,\mu,\tau}$ flavors can be detected.

$\nu_e + d \rightarrow e^- + p + p$

$\nu_x + d \rightarrow \nu_x + p + n$

2002-2003
Charged current

Neutral current

SNO Detector evidence of $\nu_e$ Oscillations from Sun to the Earth

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\( \nu_e \) and anti-\( \nu_e \) appearance probabilities (T2K)

The appearance Prob's for Neutrinos and anti-neutrinos Depend on \( \delta_{\text{CP}} \) and THEY ARE DIFFERENT IF \( \delta_{\text{CP}} \neq 0, \pi \).

We plot the probabilities for neutrino (RED) for anti-neutrino (blue) for \( x=295 \text{km} \).

If NO CP violation \( \delta_{\text{CP}} = \text{ZERO} \) then \( P = \sim 5\% \) and are equal.

If CP violation, ex. \( \delta_{\text{CP}} = 3\pi/2 \), then predictions are

\[
\begin{align*}
P(\bar{\nu}) &= \sim 6.5\% \, (\text{excess}) \\
P(\nu) &= \sim 3.5\% \, (\text{deficit})
\end{align*}
\]

ASSUME
\[
\begin{align*}
\theta_{12} &= 34^\circ \\
\theta_{23} &= 45^\circ \\
\theta_{13} &= 9^\circ \\
(\Delta m^2)_{12} &= 7.6E-5 \\
(\Delta m^2)_{23} &= 2.4E-3 \\
x &= 295 \text{ km} \\
E_\nu &= 0.6 \text{ GeV}
\end{align*}
\]
How Neutrinos are Produced

1) Nuclear beta decay; electron type anti-neutrinos from reactors
   1) Neutrons decays into proton, electron, and anti-$\nu_e$.

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

2) Pion Decay; protons incident on target produce pions and kaons which decay into leptons including muon type $\nu$ or anti-$\nu$;

\[
    \pi^+, K^+ \rightarrow \mu^+ \ \nu_\mu \hspace{1cm} \text{OR} \hspace{1cm} \pi^-, K^- \rightarrow \mu^- \ \bar{\nu}_\mu
\]

- Intense Proton beam
- TARGET
- Toroidal magnet
- Decay Volume
- Hadron Absorber

pion/kaon charge is selectable by toroidal magnet polarity so neutrino or anti-neutrino is selectable.
At off-axis angles, the $E_\nu$ peaks are particular values.
1) Scintillator Detectors
   1) Reactor detectors KamLand/DCHOOZ/Daya Bay/RENO and Nova
      1) Liquid Scintillators
   2) T2K ND280/MINOS
      1) Plastic scintillator layers alternating with water/lead/steel
   3) Nova
      1) Large Liquid scintillator modules

2) Cherenkov Detectors
   1) Super Kamiokande
      1) Large water volume lined with PMT’s
   2) ICECUBE
      1) Strings of PMT’s in south pole ice

3) OTHER methods
   1) Radio chemical; Ray Davis Expt at Homestake
   2) Detection of radio waves from large neutrino showers
   3) microBoone, DUNE; liquid argon
T2K Physics Goals are
1) $\nu_\mu \rightarrow \nu_e$ oscillation & determine $\theta_{13}$.
2) $\nu_\mu \rightarrow \nu_\mu$ oscillation & improve $\Delta m^2_{23}$ & $\theta_{23}$

$E_\nu = \sim 0.6$ GeV and $L=295$ km
ND280 Detector (neutrino beam monitor) magnet in open position
POD; pizero detector
TPC1,2,3; time projection chamber
FGD1,2; fine grain detector
DsECAL; downstream electromagnetic calorimeter
Barrel ECAL; barrel electromagnetic calorimeter
Underground tank of 50,000 tons of water lined with 11,000 phototubes. The tank is 119’ high by 111’ diameter. Observes Cerenkov light of secondary particles
**T2K ν beam results**

\[ \nu_\mu \rightarrow \nu_\mu \]

\[ \nu_\mu \rightarrow \nu_e \]

Observed 120 events, expected unoscillated
446 events. A fit to T2K data extracts the
Parameters,

\[
\sin^2(\theta_{23}) = 0.511 \pm 0.055
\]

\[
\Delta m_{23}^2 = (2.51 \pm 0.010) \times 10^{-3} \text{eV}^2
\]

Observed 28 events, (estimated 4.92 background)

Expected 21.6 events if
\[ \delta_{\text{CP}}=0, \ \theta_{13}=9^\circ \text{ and } \theta_{23}=45^\circ. \]
So evidence has slight excess.
T2K anti-$\nu$ beam results*

Observed 3 events. Expect to see 4.32 (1.68 bkgd) if $\delta_{CP}=0$, $\theta_{13}=9^\circ$ and $\theta_{23}=45^\circ$. So anti-$\nu$ evidence does not have excess.

Observed 34 events, expected 103 w/o oscillation. A fit to T2K data yields parameters,

$$\sin^2(\overline{\theta}_{23}) = 0.46^{+0.14}_{-0.06}$$
$$\Delta m_{23}^2 = (2.51^{+0.3}_{-0.2}) \times 10^{-3} \text{ eV}^2$$

Agreement between $\nu$ and anti-$\nu$ results
Are predicted by CPT invariance of mixing.

*EPS conference, July 15, 2015
NOVA Experiment

Nova Far Detector At Ash River

$E_v = 2 \text{ GeV}$
$L = 810 \text{ km}$
NOvA event candidate
Observe 33 events and expect to see 201 w/o oscillation. A fit to Nova data yields parameters,

\[
\sin^2(\theta_{23}) = 0.51 \pm 0.10
\]

\[
\Delta m^2_{23} = (2.37^{+0.16}_{-0.15}) \times 10^{-3} \text{ eV}^2
\]

Two analysis selections find 6 (LID, dark arrows) and 11 (LEM) events. Background is 0.94±0.09 events. Expected 6±0.7 events if \( \delta_{CP} = 3\pi/2 \), \( \theta_{13} = 9^\circ \) and \( \theta_{23} = 45^\circ \). So slight excess if \( \delta_{CP} = 3\pi/2 \).

*FERMILAB seminar, Aug. 6, 2015*
**SUMMARY**

$\nu_\mu$ disappearance

- T2K $\nu$ beam
  \[ \sin^2(\theta_{23}) = 0.511 \pm 0.055 \text{ and } \Delta m_{23}^2 = (2.51 \pm 0.010) \times 10^{-3} \, eV^2 \]
- T2K anti-$\nu$ beam
  \[ \sin^2(\overline{\theta}_{23}) = 0.46^{+0.14}_{-0.06} \text{ and } \Delta m_{23}^2 = (2.51^{+0.3}_{-0.2}) \times 10^{-3} \, eV^2 \]
- Nova $\nu$ beam
  \[ \sin^2(\theta_{23}) = 0.51 \pm 0.10 \text{ and } \Delta m_{23}^2 = (2.37^{+0.16}_{-0.15}) \times 10^{-3} \, eV^2 \]

$\nu_e$ appearance

- T2K $\nu$ beam
  Obs. 28 events, (est. 4.92 bkgd) expect 21.6 events if $\delta_{CP}=0$
- T2K anti-$\nu$ beam
  Obs. 3 events, (est. 1.68 bkgd) expect 4.32 events if $\delta_{CP}=0$
- Nova $\nu$ beam
  Obs. 6 events, (est. 0.94 bkgd) expect 6 events if $\delta_{CP}=3\pi/2$
With very limited statistical significance, $\delta_{CP} = 3\pi/2$, is preferred in the neutrino appearance results.

$6.57 \times 10^{20} \text{ POT}$
Marginalized over $\sin^2 \theta_{23}$ and
$\Delta m^2_{32}$ from T2K Run3 $\nu_\mu$ Results
$\sin^2 2\theta_{13} = 0.098 \pm 0.013$ (2012 PDG)
Even if neutrino’s velocity < c, There are now many neutrino jokes!!!

-If neutrinos travel faster than light does that explain why physicists never saw it coming?

-A neutrino and a photon walk into a bar. And for the next 60 nanoseconds the neutrino complains about how dark it is.

-“We don’t allow faster than light neutrinos in here” said the bartender. A neutrino walks into a bar