Status of Long-baseline Neutrino Experiments

S Uma Sankar

Department of Physics
Indian Institute of Technology Bombay
Mumbai, India
If any neutrino oscillation experiment has source to detector distance more than 100 km, we call it **long-baseline** experiment.

Sources can be natural (the Sun or the Atmosphere) or man-made (Reactors or Accelerators).

In this talk, I will limit myself to long-baseline accelerator neutrino experiments.

**A Further Classification:**
- Past (MINOS and MINOS+)
- Present (T2K and NOvA)
- Future (Hyper-K and DUNE).
I will limit myself to the oscillations of three active neutrinos.

I will not consider Reactor Anti-neutrino anomaly, LSND anomaly and Mini-BooNE anomaly.

The mixing between three active flavour eigenstates to three mass eigenstates is given by the unitary PMNS Matrix $U$.

This matrix is parametrized in terms of three mixing angles $\theta_{12}$, $\theta_{13}$ and $\theta_{23}$ and one CP-violating phase $\delta_{\text{CP}}$ as

$$U = \begin{bmatrix}
1 & 0 & 0 \\
0 & c_{23} & s_{23} \\
0 & -s_{23} & c_{23}
\end{bmatrix} \begin{bmatrix}
c_{13} & 0 & s_{13}e^{-i\delta} \\
0 & 1 & 0 \\
-s_{13}e^{i\delta} & 0 & c_{13}
\end{bmatrix} \begin{bmatrix}
c_{12} & s_{12} & 0 \\
-s_{12} & c_{12} & 0 \\
0 & 0 & 1
\end{bmatrix},$$

where $c_{ij} = \cos \theta_{ij}$ and $s_{ij} = \sin \theta_{ij}$. 
The oscillation probability for a neutrino of flavour $\alpha$ to oscillate into a neutrino of flavour $\beta$ is given by

$$P_{\alpha\beta} = \delta_{\alpha\beta} - 4 \sum_{j<i} 4 \text{Re} \left( U_{\alpha i} U_{\beta i}^* U_{\alpha j}^* U_{\beta j} \right) \sin^2 \left( 1.27 \frac{\Delta m_{ij}^2 L}{E} \right)$$

$$-2 \text{Im} \left( U_{\alpha i} U_{\beta i}^* U_{\alpha j}^* U_{\beta j} \right) \sin \left( 2.54 \frac{\Delta m_{ij}^2 L}{E} \right),$$

where $\Delta_{ij} = m_i^2 - m_j^2$ in eV$^2$, $E$ is the neutrino energy in GeV and $L$ is the distance between neutrino source and detector in km.

$U_{\alpha i}$ in the above expression of the PMNS matrix elements which can be expressed in terms of the mixing angles and the CP phase.
Effective Two-flavour Oscillations

- Given that there are three masses, there are three independent mass-squared differences, \( \Delta_{21} = m_2^2 - m_1^2 \) and \( \Delta m_3^2 - m_1^2 \).

- Solar and reactor neutrino experiments have shown that \( \Delta_{21} \approx +10^{-4} \text{ eV}^2 \).

- Atmospheric and accelerator neutrino experiments have shown that \( |\Delta_{31}| \approx 10^{-3} \text{ eV}^2 \).

- Since, \( \Delta_{21} \ll |\Delta_{31}| \), we can neglect \( \Delta_{21} \) whenever \( \Delta_{21} L/E \ll 1 \).

- This reduces the complicated three flavour oscillation formula to effective two flavour oscillation formulae in a number of cases.

- This has led to precise measurements of \( \Delta_{21} \), \( |\Delta_{31}| \), \( \sin^2 2\theta_{12} \), \( \sin^2 2\theta_{13} \) and \( \sin^2 2\theta_{23} \).
Long-baseline Neutrino Experiments (Past): MINOS

In this experiment, a $\nu_\mu$ beam from Fermilab was directed to MINOS detector 732 km away. Under the approximation of neglecting $\Delta_{21}$ and $\theta_{13}$, MINOS made precise measurements of $|\Delta_{31}$ and $\sin^2 2\theta_{23}$. 

![Diagram showing oscillation parameters for MINOS and Super-K experiments]
Long-baseline Neutrino Experiments (Past): MINOS+

The MINOS+ experiments improved on these results.
MINOS measured $\sin^2 2\theta_{23}$ quite accurately, with an uncertainty less than 0.1.

But, there is a large uncertainty in the value of $\sin^2 \theta_{23}$, as we see from MINOS+ results, because $\sin^2 2\theta_{23} \simeq 1$.

In particular, we can have $\sin^2 \theta_{23} < 0.5$ or $\sin^2 \theta_{23} > 0.5$.

This is called $\theta_{23}$ octant ambiguity.

Only the magnitude of $\Delta_{31}$ is known but not its sign. This is called hierarchy ambiguity.

Both MINOS and MINOS+ were designed to measure $P(\nu_\mu \rightarrow \nu_\mu)$ accurately, which is not sensitive to the CP violating phase.

The biggest unknown is $\delta_{CP}$. 
Both these experiments are designed to observe muon neutrino disappearance and electron neutrino appearance.

Each of them can measure four probabilities:

$$P(\nu_\mu \rightarrow \nu_\mu) \text{ and } P(\bar{\nu}_\mu \rightarrow \bar{\nu}_\mu)$$

$$P(\nu_\mu \rightarrow \nu_e) \text{ and } P(\bar{\nu}_\mu \rightarrow \bar{\nu}_e)$$

Measurement of the survival probabilities improves the precision on $|\Delta_{31}|$ and $\sin^2 2\theta_{23}$ and can tell whether $\theta_{23}$ is maximal or not.

CP violation leads to a difference between the oscillation probabilities of neutrinos and anti-neutrinos.

Hence, measuring both of them is crucial to establish CP violation in neutrino oscillations.

But, matter effects mimic CP violation, which makes the job difficult.
The $\nu_\mu \rightarrow \nu_e$ and $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ oscillation probabilities are sensitive to all the three unknowns.

This is both good news and bad news.

Good news because all three knowns can be measured in one experiment.

Bad news because the change in the probability, due to the effect of one unknown can be cancelled by the effect of another unknown.

Have to do a set of very careful measurements to disentangle the effects due to different unknowns.
Including the matter effects, the three flavour oscillation probability is

\[
P_{\mu e}^m = \sin^2 \theta_{23} \sin^2 2\theta_{13} \frac{\sin^2[(1 - \hat{A})] \tilde{\Delta}}{(1 - \hat{A})^2} + \alpha \tilde{J} \cos(\tilde{\Delta} + \delta_{CP}) \frac{\sin(1 - \hat{A}) \tilde{\Delta} \sin(\hat{A} \tilde{\Delta})}{[(1 - \hat{A})] \hat{A}},
\]

where \( \alpha = \Delta_{21}/\Delta_{31} \) and \( \tilde{J} = \cos \theta_{13} \sin 2\theta_{12} \sin 2\theta_{13} \sin 2\theta_{23} \).

In the above equation, we have used the notation \( \hat{A} = A/\Delta_{31} \) and \( \tilde{\Delta} = (\Delta_{31} L)/(4E) \), where \( A \) is the Wolfenstein matter term.

In the case of anti-neutrinos, we can obtain \( P_{\mu \bar{e}}^{mat}(\bar{\nu}_\mu \rightarrow \bar{\nu}_e) \equiv P_{\bar{\mu} \bar{e}}^m \) by the replacements \( \hat{A} \rightarrow -\hat{A} \) and \( \delta_{CP} \rightarrow -\delta_{CP} \).
We need $\theta_{13} \neq 0$ for $P_{\mu e}^m$ (and $P_{\bar{\mu} \bar{e}}^m$) to be non-zero.

The $\sin^2 \theta_{23}$ factor in the leading term makes it sensitive to the octant of $\theta_{23}$.

If $\Delta_{31}$ is positive, it is called Normal Hierarchy and if it is negative, it is called Inverted Hierarchy.

If the sign of $\Delta_{31}$ is changed, $\hat{A} \rightarrow -\hat{A}$ and $\alpha \rightarrow -\alpha$, making it sensitive to hierarchy.

The $\delta_{\text{CP}}$ dependence appears only in the sub-leading term.

This is a consequence of the fact that CP-violation is unobservable if any one of the mass-squared differences vanishes.
Current Long-Baseline Experiments: T2K and NOvA

- T2K has a narrow band beam of neutrinos, with peak flux at $E = 0.6$ GeV, from JPARC to Super-Kamiokande detector 295 km away.
- They have taken data in neutrino mode with $14.9 \times 10^{20}$ POT and in anti-neutrino mode with $16.4 \times 10^{20}$ POT. (Protons on Target)
- NOvA far detector receives narrow band neutrino beam, with peak flux at $E = 2$ GeV, from Fermilab 810 km away.
- So far, NOvA collected data with $13.6 \times 10^{20}$ POT in neutrino mode and $12.5 \times 10^{20}$ POT in anti-neutrino mode.
- Both experiments have near detectors to monitor the neutrino fluxes and to measure the interaction cross sections.
- Their analysis of $\nu_\mu / \bar{\nu}_\mu$ disappearance (based on the survival probabilities) agree with each other.
- **T2K**: $\Delta_{31} = (2.54 \pm 0.07) \times 10^{-3}$ eV$^2$ and $\sin^2 \theta_{23} = 0.53 \pm 0.04$.
- **NOvA**: $\Delta_{31} = (2.48 \pm 0.07) \times 10^{-3}$ eV$^2$ and $\sin^2 \theta_{23} = 0.57 \pm 0.03$. 
T2K observes a total of 90 $\nu_e$ appearance events and 15 $\bar{\nu}_e$ appearance events. Nature 580 (2020) 7803, 339-344, Nature 583 (2020) 7814, E16 (erratum); e-Print: 1910.03887

T2K data strongly prefers that the octant is higher and $\delta_{CP} \simeq -\pi/2$.

In fact, T2K claim to rule out $\delta_{CP} = 0$ at 99.79% (3 $\sigma$) confidence level.
Results of T2K Appearance data (2018)
NOvA observes 82 $\nu_e$ appearance events and 33 $\bar{\nu}_e$ appearance events.

The best fit point is (NH, HO with $\sin^2 \theta_{23} = 0.57$, $\delta_{CP} = 5\pi/6$).

But, multiple solutions with (NH, LO), (NH, HO), (IH, LO) and (IH, HO) are all acceptable at 68% ($1\sigma$) confidence level.

So there is a strong tension between the appearance data of T2K and NOvA.

Eventhough, the best-fit points of both T2K and NOvA choose normal hierarchy, a fit to the combined data of the two experiments prefers inverted hierarchy.

Best Fit
Normal hierarchy
\[ \Delta m^2_{32} = (2.41 \pm 0.07) \times 10^{-3} \text{ eV}^2 \]
\[ \sin^2 \theta_{23} = 0.57^{+0.04}_{-0.03} \]
\[ \delta = 0.82\pi \]
We see no strong asymmetry in the rates of appearance of $\nu_e$ and $\bar{\nu}_e$.

Disfavor hierarchy-$\delta$ combinations which would produce that asymmetry.

Consistent with hierarchy-octant-$\delta$ combinations which include some "cancellation."

- Since such options exist for both octants and hierarchies, results show no strong preferences.

Exclude IH $\delta = \pi/2$ at $>3\sigma$

Disfavor NH $\delta = 3\pi/2$ at $\sim2\sigma$

Prefer...
- Normal Hierarchy at $1.0\sigma$
- Upper Octant at $1.2\sigma$
Tension Between Appearance Data of T2K and NOvA

Comparison to T2K

Normal Hierarchy

- Clear tension with T2K’s preferred region.
- Quantifying consistency requires a joint fit of the data from the two experiments, which is already in the works.
  - Semi-annual workshops, regular joint group meetings, and a signed joint agreement.
We define a hypothetical reference point: No matter effects, No CP Violation and $\sin^2 \theta_{23} = 0.5$.

For this reference point, T2K is expected to have $60$ $\nu_e$ appearance and $20$ $\bar{\nu}_e$ appearance events.

Data shows a large excess in $\nu_e$ and a small shortfall in $\bar{\nu}_e$ events.

This can happen only if hierarchy is normal, $\sin^2 \theta_{23} > 0.5$ and $\delta_{CP} \approx -90^\circ$.

In the case of NOvA, there is $\sim 30\%$ excess, compared to the reference point in both $\nu_e$ and $\bar{\nu}_e$ events.

This points to EITHER normal hierarchy and $\delta_{CP}$ in upper half plane OR inverted hierarchy and $\delta_{CP}$ in lower half plane.
Shortcomings of the Present Experiments

- The energy of T2K is very low (about 0.6 GeV) and it has very little sensitivity to matter effect.
- In the case of NOvA, the matter effect leads to a change in appearance probability of about $\sim 25\%$.
- But the changes induced by matter effects and the change induced by changing $\delta_{CP}$ from zero to maximal value is the same.
- Impossible to disentangle this hierarchy-$\delta_{CP}$ degeneracy in NOvA.
Long-baseline Neutrino Experiments (Future): Hyper-K and DUNE

- In Hyper-K, the baseline and the neutrino energy will be the same as that T2K but it will be a very massive detector.
- They expect to determine hierarchy using atmospheric neutrino data and the octanct and $\delta_{CP}$ using accelerator data.
- DUNE will have a baseline of about 1300 km and energy of peak flux of about 3 GeV.
- The higher energy leads to a larger matter effect, which will be larger than the change induced by changing $\delta_{CP}$ from zero to maximal value.
- They expect to resolve the hierarchy-$\delta_{CP}$ tangle through this method.
- Both are very high statistics experiments with very sensitive instrumentation for efficient event reconstruction.
Expected Results from Hyper-Kamiokande
Simulated Results from DUNE

- $\sin^2 \theta_{23} = 0.580$
- $\Delta m_{23}^2 = 2.451 \times 10^{-3} \text{ eV}^2$
- 3.5 years (staged)

**Events per 0.25 GeV**

**Reconstructed Energy (GeV)**

- Signal $\nu_\mu$ CC
- $\bar{\nu}_\mu$ CC
- NC
- $(\nu_\theta + \bar{\nu}_\theta)$ CC
- $(\nu_\tau + \bar{\nu}_\tau)$ CC
Simulated Results from DUNE

DUNE $\nu_e$ Appearance
Normal Ordering
$\sin^2 2\theta_{13} = 0.088$
$\sin^2 \theta_{23} = 0.580$
3.5 years (staged)
- Signal ($\nu_e + \bar{\nu}_e$) CC
- Beam ($\nu_e + \bar{\nu}_e$) CC
- NC
- ($\nu_\mu + \bar{\nu}_\mu$) CC
- ($\nu_\tau + \bar{\nu}_\tau$) CC

---

DUNE $\nu_e$ Appearance
Normal Ordering
$\sin^2 2\theta_{13} = 0.088$
$\sin^2 \theta_{23} = 0.580$
3.5 years (staged)
- Signal ($\nu_e + \bar{\nu}_e$) CC
- Beam ($\nu_e + \bar{\nu}_e$) CC
- NC
- ($\nu_\mu + \bar{\nu}_\mu$) CC
- ($\nu_\tau + \bar{\nu}_\tau$) CC
Conclusions

- Current experiments, T2K and NOvA, are taking data which can, in principle, determine the present unknowns of neutrino oscillations.
- The results of the $\nu_\mu/\bar{\nu}_\mu$ disappearance data of these experiments are in complete agreement.
- However, the results of $\nu_e/\bar{\nu}_e$ appearance data are in strong disagreement.
- The disagreement is partly due to neutrino data and partly due to anti-neutrino data.
- More statistics may resolve the present disagreement.
- OR Is it NEW PHYSICS?
- Future (especially Hyper-K and DUNE) will give a better picture.