Invisible neutrino decay in T2K and NOvA

Dipyaman Pramanik

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Neutrino oscillation is one of the very few evidences of physics beyond the Standard Model.

Standard neutrino oscillation physics contains three mixing angles, one CP violating phase and two mass-squared differences.

After Daya-Bay result, all the angles are non-zero.

The current unknowns are CP phase, the octant of theta23 and the sign of the atmospheric mixing angle.

There is plenty of room to explore for new physics.
Current ongoing experiments

- T2K, NOvA are the long baseline experiments
- Super-K, IceCUBE, ANTARES are examples of the atmospheric experiments
- There are reactor experiments like DayaBay, RENO, Double-CHOOZ etc.
Current situation

- Normal hierarchy is preferred
- Hint of CP violation
- Hint of maximal theta23 mixing

Octant is unknown

Unknown mass

Hierarchy

Unknown CP
Future experiments

- There are DUNE, T2HK, T2HKK, ESS, P2O in the long-baseline sector.

- There are INO, Hyper-K, Super-ORCA, PINGU etc. in the atmospheric sector.

- There are also many dedicated experiments for new physics search like SBN
Neutrino decay
Neutrino decay

Invisible decay:

\[ \nu \rightarrow S \] (sterile state)

If neutrinos are Dirac:

\[ \nu_j \rightarrow \bar{\nu}_{iR} + \chi \]

\( \chi \) is iso-singlet scalar
\( \bar{\nu}_{iR} \) is right-handed singlet

If neutrinos are Majorana:

\[ \nu_j \rightarrow \nu_s + J \]

\( \bar{\nu}_s \) is a sterile neutrino
\( J \) is a Majoron
Neutrino decay

Visible decay:

\[ \nu \rightarrow \bar{\nu} + J \]

Two decay modes:

\[ \nu_j \rightarrow \bar{\nu}_i + J \]
\[ \nu_j \rightarrow \nu_i + J \]

In this case J is also coupled to the charged lepton.

Heavily constrained from the K-decay bounds.
Propagation in presence of decay:

We assume $\nu_3$ to decay into $\bar{\nu}_4$ and a singlet scalar $J$

$$\nu_3 = \bar{\nu}_4 + J$$

$$\begin{pmatrix} \nu_\alpha \\ \nu_s \end{pmatrix}$$

Now, the flavour and mass basis get related as

$$\begin{pmatrix} \nu_\alpha \\ \nu_s \end{pmatrix} = \begin{pmatrix} U & 0 \\ 0 & 1 \end{pmatrix} \begin{pmatrix} \nu_i \\ \nu_4 \end{pmatrix}$$

$U$ is the standard PMNS matrix
The effect of decay can be incorporated in the evolution equation by:

\[ i \frac{d}{dx} \begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \left[ U \begin{pmatrix} 0 & 0 & 0 \\ 0 & \Delta m^2_{21} & 0 \\ 0 & 0 & \Delta m^2_{31} \end{pmatrix} - i \frac{m_3}{2E\tau_3} \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 1 \end{pmatrix} \right] U^\dagger \begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} + \begin{pmatrix} A & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \end{pmatrix} \begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} \]

decay lifetime is \( \tau_3 \)

Note: Here we assume that the mass matrix and the decay matrix can be simultaneously diagonalised.
Constraints from long-baseline experiments

<table>
<thead>
<tr>
<th>Experiment</th>
<th>Value</th>
<th>POT</th>
<th>Mode</th>
</tr>
</thead>
<tbody>
<tr>
<td>MINOS</td>
<td>$10.71 \times 10^{20}$</td>
<td>POT</td>
<td>$\nu_\mu$</td>
</tr>
<tr>
<td></td>
<td>$3.36 \times 10^{20}$</td>
<td>POT</td>
<td>$\bar{\nu}_\mu$</td>
</tr>
<tr>
<td></td>
<td>$7.07 \times 10^{20}$</td>
<td>POT</td>
<td>NC</td>
</tr>
<tr>
<td>T2K</td>
<td>$6.57 \times 10^{20}$</td>
<td>POT</td>
<td>$\nu_\mu$</td>
</tr>
</tbody>
</table>

$\tau_3/m_3 = 8.48 \times 10^{-12}$ s/eV

T2K (Tokai to Kamiokande)
- 30 GeV Proton beam from J-Parc accelerator to Kamiokande detector. (295 km)
- 22.5 kt water Cherenkov detector. (Super Kamiokande)
- 2.5 degree off-axis beam to give narrow spectrum

NOvA
- NuMI beam at Fermilab to 810 km near Ash river, Minnesota.
- 14 kt scintillator detector.
- 14.6 mrad off-axis beam to give narrow spectrum.
Constraints from T2K & NOvA

Before Nu18

NOvA

$6.04 \times 10^{20}$ POT $\nu_e$

$8.85 \times 10^{20}$ POT $\nu_\mu$

T2K

$7.482 \times 10^{20}$ POT $\nu$

$7.741 \times 10^{20}$ POT $\bar{\nu}$

$\tau_3/m_3 = 5.01 \times 10^{-12} s/eV$

S. Choubey, D. Dutta, DP, JHEP 1808 (2018) 141
Decay vs standard fit

Important point to note:

The decay best-fit is finite: hints of decay
If we allow decay in the fit the best-fit of $\theta_{23}$ shifts towards the right.

\[ P_{\mu\mu}^{2G} = \left[ \cos^2 \theta_{23} + \sin^2 \theta_{23} \exp(-m_3 L/\tau_3 E) \right]^2 - \sin^2 2\theta_{23} \exp(-m_3 L/\tau_3 E) \sin^2 \left( \frac{\Delta m_{31}^2 L}{4E} \right) \]
T2K & NOvA cont...

\[ \Delta \chi^2 \]

\[ \Delta m^2_{32} \times 10^{-3} \text{(eV}^2) \]

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S.Choubey,D.Dutta, DP , JHEP 1808 (2018) 141
$\Delta m^2_{32} \times 10^{-3} \text{ (eV}^2\text{)}$

$\sin^2 \theta_{23}$

- NOvA with decay
- T2K with decay
- NOvA std
- T2K std
- Combined std
- combined with decay

S.Choubey, D.Dutta, DP, JHEP 1808 (2018) 141
Future

S. Choubey, S. Goswami, DP, JHEP 1802 (2018) 055

DUNE

INO

Choubey et. al, PRD 97 (2018)
Conclusion

- Among the six standard oscillation parameters, there are three unknowns, the $\delta_{CP}$, octant of $\theta_{23}$ and the sign of $\Delta m_{31}^2$.

- Invisible neutrino decay can be a new physics option to explore.

- There are some hints of neutrino decay from the long-baseline experiments.

- The presence of decay can alter the measurement of standard oscillation parameters like $\theta_{23}$ & $\Delta m_{31}^2$.

- IceCUBE track and cascade tension can be explained in terms of decay.

- Future long-baseline as well as atmospheric experiments can be nice probe to explore the decay scenario.
thank you
Current constraints:

Bound on $\frac{\tau_2}{m_2}$ from solar neutrino data

$$\frac{\tau_2}{m_2} > 8.5 \times 10^{-7} \text{(s/eV)}$$


SN1987A supernova data puts bound of

$$\frac{\tau_2}{m_2} > 10^{-5} \text{(s/eV)}$$


MINOS, T2K data give bounds on $\frac{\tau_3}{m_3}$

$$\frac{\tau_3}{m_3} > 2.8 \times 10^{-12} \text{(s/eV)} \quad 90 \% \text{ C.L}$$


Expected sensitivity from JUNO:

$$\frac{\tau_3}{m_3} > 7.5 \times 10^{-11} \text{(s/eV)} \quad 95 \% \text{ C.L}$$

[JHEP 1511 (2015) 001]

Expected sensitivity from 100 TeV neutrino from 1 Gpc source at IceCUBE

$$> 10 \text{(s/eV)}$$

A bit of History

- Neutrino decay as a solution to atmospheric neutrino problem was first proposed in hep-ph/9809499.

- Visible decay with mixing was proposed in order to explain atmospheric neutrino in PRL 82 (1999), hep-ph/9904257.

- Invisible decay with two options:
  - Unconstrained $\Delta m^2$ (Choubey et al. hep-ph/9904257)
  - $\Delta m^2 \ll 10^{-4} \text{eV}^2$ (Ruled out by SK Collab. hep-ph/9907421)

Without oscillation

Ruled out by SK collab.
Ice Cube Results