Short-baseline Neutrino Oscillations

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Neutrino Oscillation

Sterile neutrinos

$\nu_e$, $\bar{\nu}_e$ appearance results, present and future

$\nu_\mu$, $\bar{\nu}_\mu$ disappearance results, present and future

Summary
Neutrino Oscillation Intuition

Neutrino oscillation is much like a double slit experiment; the neutrino mass eigenstates propagate differently, and interfere.

Given an initial flavor eigenstate of $\nu_\mu$, observation some time later will yield a combination which:

1) has maximal $\nu_e$ (constructive interference) or
2) has only $\nu_\mu$ (destructive interference)

The amount of interference is governed by the mixing matrix, $U$

No mass means no interference is possible.
Two-Neutrino Oscillation

If there are just two mass eigenstates, $\nu_1$ and $\nu_2$ and two flavor eigenstates, $\nu_e$ and $\nu_\mu$, then $U$ is a rotation matrix between mass and flavor:

$$U = \begin{pmatrix} U_{\mu 1} & U_{e 1} \\ U_{\mu 2} & U_{e 2} \end{pmatrix} = \begin{pmatrix} \cos \theta & \sin \theta \\ -\sin \theta & \cos \theta \end{pmatrix}$$

The probability to observe $\nu_e$ with a pure $\nu_\mu$ sample is:

$$P_{e \to \mu} = |\langle \nu_e | \nu_\mu(t) \rangle|^2 = \sin^2 2\theta \sin^2 \left( 1.27 \frac{\Delta m_{12}^2}{E} \frac{L}{E} \right)$$

where $L$ (km) is the distance traveled, $E$ (GeV) is the energy of the neutrino and $\Delta m^2$ (eV$^2$) is the “mass splitting” difference of the masses squared:

$$\Delta m_{12}^2 = m_1^2 - m_2^2$$

Short baseline (L~1km) vs Long baseline (L~100-1000km) vs Solar (L~1AU)
Neutrino oscillation can be observed via “appearance” or “disappearance”

Disappearance experiment: Detect fewer $\nu_\mu$ than expected from a $\nu_\mu$ source
Example: MINOS Experiment (long baseline experiment)
3.6 $\sigma$ deficit of $\nu_\mu$ events for $\Delta m^2 \sim 10^{-3} \text{eV}^2$, $\theta \sim 45^\circ$

- Signature for neutrino oscillation is a distortion of the neutrino energy spectrum
  Neutrinos at energy $E_1$ oscillate differently than at $E_2$ for the same $L$
- Depends on understanding of $\nu_\mu$ event rate: flux $\times$ cross section $\times$ efficiency
Neutrino oscillation can be observed via “appearance” or “disappearance”

**Appearance experiment:** Detect more $\nu_e$ than expected from a $\nu_\mu$ source

**Example:** LSND Experiment

Observation of $3.8 \sigma$ excess of $\bar{\nu}_e$ in $\bar{\nu}_\mu$ beam, $\Delta m^2 \sim 1 \text{eV}^2$, $\theta \sim 1-10^\circ$
Since there are three observed flavors of neutrinos ($\nu_e$, $\nu_\mu$, $\nu_\tau$), the mixing matrix, $U$, contains three mixing angles ($\theta_{12}, \theta_{23}, \theta_{13}$) and a CP violating phase $\delta$.

$$
\begin{pmatrix}
\nu_e \\
\nu_\mu \\
\nu_\tau
\end{pmatrix} =
\begin{pmatrix}
U_{e1} & U_{e2} & U_{e3} \\
U_{\mu1} & U_{\mu2} & U_{\mu3} \\
U_{\tau1} & U_{\tau2} & U_{\tau3}
\end{pmatrix}
\begin{pmatrix}
\nu_1 \\
\nu_2 \\
\nu_3
\end{pmatrix}
$$

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

"Atmospheric": $\Delta m_{23}^2 \sim 10^{-3} \text{eV}^2$, $\theta_{23} \sim 45^\circ$

Observed with atmospheric $\nu$, confirmed with accelerator $\nu$

"Reactor": $\theta_{13} < 13^\circ$

Not observed yet

"Solar": $\Delta m_{12}^2 \sim 10^{-5} \text{eV}^2$, $\theta_{12} \sim 32^\circ$

Observed with solar $\nu$, confirmed with reactor $\nu$

Recent results (B. Rebel)

Recent results (M. Pallavicini)
Three-Neutrino Oscillation

Since there are three observed flavors of neutrinos ($\nu_e$, $\nu_\mu$, $\nu_\tau$), the mixing matrix, $U$, contains three mixing angles ($\theta_{12}$, $\theta_{23}$, $\theta_{13}$) and a CP violating phase $\delta$.

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu1} & U_{\mu2} & U_{\mu3} \\ U_{\tau1} & U_{\tau2} & U_{\tau3} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

“Atmospheric”: $\Delta m^2_{23} \sim 10^{-3} \text{eV}^2$, 
$\theta_{23} \sim 45^\circ$

“Solar”: $\Delta m^2_{12} \sim 10^{-5} \text{eV}^2$, 
$\theta_{12} \sim 32^\circ$

There are two independent $\Delta m^2$, as $\Delta m^2_{12} + \Delta m^2_{23} = \Delta m^2_{13}$

LSND observed $\Delta m^2 \sim 1\text{eV}^2 \gg \Delta m^2_{12} + \Delta m^2_{23}$

Inconsistent with just three mass eigenstates
**Sterile Neutrinos**

One explanation for the LSND oscillation signal is to add another “sterile” flavor of neutrino (or 2 or N) to the neutrino mixing matrix:

Adding 1 sterile neutrino is 3+1, adding N is 3+N

\[
U_{\alpha i} = \begin{pmatrix}
    v_e \\
v_\mu \\
v_\tau \\
v_s
\end{pmatrix}
\begin{pmatrix}
    U_{e1} & U_{e2} & \cdots & U_{eN} \\
    U_{\mu 1} & U_{\mu 2} & \cdots & U_{\mu N} \\
    U_{\tau 1} & U_{\tau 2} & \cdots & U_{\tau N} \\
    \vdots & \vdots & \ddots & \vdots \\
    v_1 \\
v_2 \\
v_3 \\
v_N
\end{pmatrix}
\]

Independent of LSND, neutrino oscillation implies non-zero neutrino mass

Most models introduce a right handed neutrino, which by definition would not couple to W, Z and avoid the constraints from LEP

Such neutrinos could interact only via oscillation
The lack of $\nu_\mu$ disappearance observed by CDHS and CCFR experiments and the Bugey and Chooz reactor experiments ($\bar{\nu}_e \rightarrow \bar{\nu}_x$) disfavor the addition of 1 sterile neutrino (3+1)


Note: $\sin^2 2\theta / 4 \sim \sin^2 \theta$ for small $\theta$

$\sin^2 \theta = |U_{\mu 4}|^2$
Constraints from Reactors

Previous (single) detector reactor experiments use inverse beta decay to look for energy dependant $\bar{\nu}_e$ disappearance

$$\bar{\nu}_e + p \rightarrow e^+ + n$$
$$n + p \rightarrow d + \gamma$$

Future reactor experiments employ multiple detectors at powerful reactors around the world to measure $\theta_{13}$

**RENO** (Poster by B.C. Kim) 2 detector sites, 16.4 GW

**Daya Bay** (Poster by C.Y. Wang) 3 detector sites, 11.6 GW

**Double Chooz** 2 detector sites, 8.5 GW

They will also constrain $U_{e4}$
Constraints from LBL experiments

LBL experiments constrain the sterile content as well

Test of Lorentz Invariance and CPT conservation with Minos near detector
Look for sidereal modulation in neutrino rate \( \Rightarrow \) consistent with no modulation

Test of active/sterile oscillations at Minos far detector
Check for deficit of NC interactions due to \( \nu_\mu \rightarrow \nu_s \) conversion

\[
\frac{f_s}{1 - P_{\nu_\mu \rightarrow \nu_\mu}} \sim < 50\% \quad (90\% CL)
\]

Fraction of sterile neutrinos from \( \nu_\mu \)
\( \Rightarrow \) consistent with no sterile oscillation

\( \text{Phys.Rev.Lett.101:151601,2008} \)
MiniBooNE Experiment

Similar L/E designed to test LSND-like $\nu_e$ appearance

*Different event signature and backgrounds than LSND*

8.9 GeV/c protons on Be produce mesons which decay to neutrinos (or antineutrinos) detected in a ~1kton mineral oil Cherenkov detector

*Changing the polarity of the magnetic horn focuses positive (negative) mesons which decay to produce a beam of neutrinos (antineutrinos)*

Since August 2002, MiniBooNE has collected:

- $6.5 \times 10^{20}$ POT (neutrino) fully analyzed
- $5.1 \times 10^{20}$ POT (antineutrino) $3.4 \times 10^{20}$ POT analyzed
Use hit topology, timing to determine event type

- Outgoing lepton implies flavor of neutrino for charged current events
- **Reconstructed quantities**: track length, angle relative to beam direction
- **Fundamental**: timing, charge of hits, early/late hit fractions
- **Geometry**: position from wall of tank

Selection of electron-like rings implies electron neutrino candidates, selection of muon-like rings implies muon neutrino candidates

Identical selection for neutrino and antineutrino events
MiniBooNE Oscillation Analyses

Search for $\nu_e$, $\bar{\nu}_e$ appearance
  Direct test of LSND observed excess

Search for $\nu_\mu$, $\bar{\nu}_\mu$ disappearance
  Complementary channel
  Constrains sterile neutrino models

The combination of $\nu$ and $\bar{\nu}$ results tests unitarity of the mixing matrix, and CPT
Search for an excess of $\nu_e$ events over expected backgrounds

- Beam $\nu_e$ from $K^{+/0}$ decay
- Misreconstructed $\pi^0$
- Beam $\nu_e$ from $\mu$ decay

Uncertainties on backgrounds reduced from $\nu_\mu$ event samples

$\nu_e$ sample is consistent with expectation in LSND region $E_\nu > 475$ MeV (0.6 $\sigma$ excess)

Simple 2 neutrino oscillations excluded at 98% CL  

$\nu_e$ appearance results  


Unexpected excess of events below 475 MeV
Improved $\nu_e$ appearance results

Extensive checks and additions to analysis

1) Improved $\pi^0$ prediction
2) Additional “photonuclear” absorption background included
3) Improved analysis cuts to reduce backgrounds further
4) Increased statistics
   $5.6 \Rightarrow 6.5 \times 10^{20}$ POT

Excess reduced but still present
   $(3.0 \sigma)$

MiniBooNE $\bar{\nu}_e$ appearance results

$\bar{\nu}_e$ appearance tests LSND and shares many of the same backgrounds as $\nu_e$ appearance at low energy

First result ($3.4\times10^{20}$ POT) has low statistics

Both LSND best fit and no-oscillations are allowed $\Rightarrow$ inconclusive

Additional data will help reduce substantial statistical uncertainties on $\bar{\nu}_e$ sample

But still a surprise, no indication of a low energy excess

*arXiv:0904.1958, accepted by PRL*
To explain the low energy excess in neutrino mode, one would need to increase backgrounds substantially.

Difficult to do, most backgrounds are constrained and should be the same in neutrino/antineutrino samples.

Correlated systematic uncertainties between $\nu$ / $\bar{\nu}$ in progress.

Most compatible background to match low energy excess is one which scales with neutrinos but not antineutrinos.
Low energy excess with $\nu_e / \bar{\nu}_e$

Theoretical models are also, similarly, disfavored if they link neutrinos and antineutrinos

**Possible explanation**

<table>
<thead>
<tr>
<th>Possible Explanation</th>
<th>Status</th>
</tr>
</thead>
<tbody>
<tr>
<td>Anomaly Mediated Neutrino-Photon Interactions:</td>
<td>Disfavored</td>
</tr>
<tr>
<td>CP-Violation 3+2 Model:</td>
<td>Possible</td>
</tr>
<tr>
<td>Lorentz Violation:</td>
<td>Possible</td>
</tr>
<tr>
<td>CPT Violation 3+1 Model:</td>
<td>Possible</td>
</tr>
<tr>
<td>VSBL Electron Neutrino Disappearance:</td>
<td>Disfavored</td>
</tr>
<tr>
<td>New Gauge Boson with Sterile Neutrinos:</td>
<td>Disfavored</td>
</tr>
</tbody>
</table>
MiniBooNE sees neutrinos from the Minos (NuMI) beam at an angle of 110 mrad off-axis. Similar L/E as MiniBooNE from production, different flux.

$\nu_\mu$ events from $\pi$, $K$

$\nu_e$ predominantly from $K^{+/0}$

Analysis in progress to constrain uncertainties on $\nu_e$ from $\nu_\mu$ sample.
MiniBooNE Oscillation Analyses

Search for $\nu_e$, $\bar{\nu}_e$ appearance
   Direct test of LSND observed excess

Search for $\nu_\mu$, $\bar{\nu}_\mu$ disappearance
   Complementary channel
   Constrains sterile neutrino models

The combination of $\nu$ and $\bar{\nu}$ results tests unitarity of the mixing matrix, and CPT
Method: Compare for $\nu_\mu$ / $\bar{\nu}_\mu$ sample to expectation

Selection of $\nu_\mu$ candidates:
Tag single muon events and their decay electron
Background is $CC\pi^+$ where the pion is absorbed in nucleus or detector

$CCQE$ $\nu_\mu$ $\mu^-$ $W^+$ $n$ $p$

$74\%$ $CCQE$ purity
$190,454$ events

Reconstructed $E_v$ (GeV)
MiniBooNE $\bar{\nu}_\mu$ disappearance

Method: Compare $\nu_\mu / \bar{\nu}_\mu$ sample to expectation

Apply same CCQE selection to antineutrino dataset

Similar $CC\pi^{+/0}$ background, and CCQE purity as in neutrino mode

Substantial neutrino events in the antineutrino sample (~25%)

![Diagram showing neutrino interactions and reconstruction of energy](image)

70% CCQE purity
27,053 events

Reconstructed $E_\nu$ (GeV)
MiniBooNE observes no evidence for neutrino or antineutrino disappearance at 90%CL

Neutrino data excludes some 3+2 models

Future work will incorporate data from a second detector, SciBooNE.

In 2007, a dedicated cross section experiment, SciBooNE, was put in the MiniBooNE beam.

Recent results (M. Yokoyama)

SciBooNE shares the same flux and detector composition as MiniBooNE (carbon).

Use SciBooNE to constrain MiniBooNE rate (Poster, Y. Nakajima)
Summary and Future

Hard to accommodate sterile neutrinos with 3+2 models and existing neutrino/antineutrino disappearance and appearance data


- Correlated MiniBooNE $\nu_e$, $\bar{\nu}_e$ appearance analysis in progress
- Joint NuMI $\nu_e$ analysis with new $\nu_\mu$ constraint

However, agreement among antineutrino experiments only is high.
Direct tests in both antineutrino appearance and disappearance channels

- Joint MiniBooNE/SciBooNE $\nu_\mu$, $\bar{\nu}_\mu$ disappearance analysis

Extended $\bar{\nu}$ running planned for MiniBooNE

Approved for ~10x10^{20} POT run with intermediate result with 5x10^{20} POT dataset
New MicroBooNE experiment approved
~70 ton fiducial volume Liquid Argon TPC
placed near MiniBooNE
TPC development combined with
physics goal of understanding low energy excess
  Reduced backgrounds
  Can distinguish if excess is photon or electron in nature
First data ~2012
Far-term future possibilities

Extension of MiniBooNE (BooNE)
   Move MiniBooNE to 200 m in beamline (~$4M) or build a second detector there (~$8M)
   Cancel many uncertainties between near, far detectors

Alternate method to study sterile neutrinos:
   low energy beta beam \( \bar{\nu}_e \) disappearance

Agarwalla, Huber, Link, arXiv.org: hep-ph 0907.3145
   Disappearance channel with inverse beta decay
   Different systematics
   Would require ~100ton detector and ion production rates of ~2x10^{13} / s
Thanks to the organizers and local committee for a wonderful conference!
Excess in different kinematic variables
\( \chi^2 \) Values from Data/MC Comparisons

<table>
<thead>
<tr>
<th>Process</th>
<th>( \chi^2(\cos \theta)/9 ) DF</th>
<th>( \chi^2(Q^2)/6 ) DF</th>
<th>Factor Inc.*</th>
</tr>
</thead>
<tbody>
<tr>
<td>NC ( \pi^0 )</td>
<td>13.46</td>
<td>2.18</td>
<td>2.0</td>
</tr>
<tr>
<td>( \Delta \rightarrow N\gamma )</td>
<td>16.85</td>
<td>4.46</td>
<td>2.7</td>
</tr>
<tr>
<td>( \nu_e , C \rightarrow e^- X )</td>
<td>14.58</td>
<td>8.72</td>
<td>2.4</td>
</tr>
<tr>
<td>( \bar{\nu}_e , C \rightarrow e^+ X )</td>
<td>10.11</td>
<td>2.44</td>
<td>65.4</td>
</tr>
</tbody>
</table>

* Any background would have to increase by >5\( \sigma \)!
Flux at MiniBooNE

Neutrino mode

- Predominantly $\nu_\mu$ - $\sim 6\%$ $\bar{\nu}_\mu$
- $\sim 0.5\%$ $\nu_e + \bar{\nu}_e$

Antineutrino mode

- Substantial $\bar{\nu}_\mu$ background - $\sim 16\%$ $\nu_\mu$
- $\sim 0.6\%$ $\nu_e + \bar{\nu}_e$

All details of the beamline geometry are modeled

At 1 GeV, neutrinos interact via
- CCQE (quasi-elastic scattering)
- CCpi+ (single pion production)

In CCQE interactions, the muon’s energy ($E_\mu$), and angle ($\theta_\mu$) are sufficient to reconstruct the neutrino energy:

$$E_\nu(QE) = \frac{m_NE_\mu - \frac{1}{2}m_N^2}{p_\mu \cos \theta_\mu + m_N - E_\mu}$$

where $m_N$ is the mass of the nucleon.