Fermilab Short-Baseline Neutrino Program

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Neutrino Oscillations

Simplified Two Neutrino Oscillations

$$P(\nu_\alpha \rightarrow \nu_\beta) = \sin^2 2\theta_{ij} * \sin^2 \left(1.27 \Delta m^2 \frac{L}{E}\right)$$

The mixing angle, $\theta$, determines the amplitude of the oscillation.

$\Delta m^2$ determines the shape of the oscillation as a function of $L$ (or $E$).

Three Neutrino Oscillations

$$\Delta m^2_{\text{atm}} = 2.43^{+0.13}_{-0.13} \times 10^{-3} \text{ eV}^2$$

$$\Delta m^2_{\text{sol}} = 7.59^{+0.20}_{-0.21} \times 10^{-5} \text{ eV}^2$$

$L/E = 500 \text{ km/GeV}$

$L/E = 15,000 \text{ km/GeV}$
Experimental data has raised questions about the validity of the 3-flavor paradigm

Anomalous results from LSND and MiniBooNE can be described by including sterile neutrinos with a mass splitting of \( \sim 1 \) eV

Oscillations involving these possible sterile neutrinos would have a characteristic L/E dependence of \( \sim 1 \) km/GeV

Studying the nature of the MiniBooNE low-energy excess is a necessity

<table>
<thead>
<tr>
<th>Experiment</th>
<th>Type</th>
<th>Channel</th>
<th>Significance</th>
</tr>
</thead>
<tbody>
<tr>
<td>LSND</td>
<td>DAR</td>
<td>( \bar{\nu}_\mu \rightarrow \bar{\nu}_e ) CC</td>
<td>3.8( \sigma )</td>
</tr>
<tr>
<td>MiniBooNE</td>
<td>SBL accelerator</td>
<td>( \nu_\mu \rightarrow \nu_e ) CC</td>
<td>3.4( \sigma )</td>
</tr>
<tr>
<td>MiniBooNE</td>
<td>SBL accelerator</td>
<td>( \bar{\nu}_\mu \rightarrow \bar{\nu}_e ) CC</td>
<td>2.8( \sigma )</td>
</tr>
<tr>
<td>GALLEX/SAGE</td>
<td>Source - e capture</td>
<td>( \nu_e ) disappearance</td>
<td>2.8( \sigma )</td>
</tr>
<tr>
<td>Reactors</td>
<td>Beta-decay</td>
<td>( \bar{\nu}_e ) disappearance</td>
<td>3.0( \sigma )</td>
</tr>
</tbody>
</table>

First proposed by Carlo Rubbia in 1977, the Liquid Argon Time Projection Chamber (LArTPC) provides bubble chamber quality imaging along with detailed calorimetry, allowing for precise particle identification using both topology and ionization energy loss.
Booster Neutrino Beam
We will use a suite of experiments to build a definitive program

- MicroBooNE will examine the MiniBooNE low-energy excess and address if it is electron or photon in nature.

- The Liquid ARgon Near Detector (LAr1-ND) and a refurbished T600 detector will allow us to address whether this signal is intrinsic to the beam or if it appears via oscillations. If the signal is due to oscillations these experiments will probe the parameters with high precision.
Liquid ARgon Near Detector (LAr1-ND)

Sitting close (~100m) to the BNB neutrino target it will provide a detailed characterization of the beam

This will allow for a near-to-far extrapolation among the program’s detectors and enabling precision searches for neutrino oscillations

From GENIE Simulations

<table>
<thead>
<tr>
<th>Process</th>
<th>$\nu_\mu$ Events</th>
<th>$\nu_e$ Events</th>
</tr>
</thead>
<tbody>
<tr>
<td>CC Inclusive</td>
<td>787,847</td>
<td>5,883</td>
</tr>
<tr>
<td>NC Inclusive</td>
<td>300,585</td>
<td>2,098</td>
</tr>
<tr>
<td>Total $\nu_\mu$ and $\nu_e$ Events</td>
<td>1,096,413</td>
<td></td>
</tr>
</tbody>
</table>

**$\nu_\mu$ Events (By Physical Process )**

<table>
<thead>
<tr>
<th>Process</th>
<th>Equation</th>
<th>No. Events</th>
</tr>
</thead>
<tbody>
<tr>
<td>CC QE</td>
<td>$\nu_\mu n \rightarrow \mu^- p$</td>
<td>470,497</td>
</tr>
<tr>
<td>CC RES</td>
<td>$\nu_\mu N \rightarrow \mu^- N$</td>
<td>220,177</td>
</tr>
<tr>
<td>CC DIS</td>
<td>$\nu_\mu N \rightarrow \mu^- X$</td>
<td>82,326</td>
</tr>
<tr>
<td>CC Coherent</td>
<td>$\nu_\mu Ar \rightarrow \mu Ar + \pi$</td>
<td>3,004</td>
</tr>
</tbody>
</table>
The discriminating power of the LArTPC we will be able to reduce the single photon backgrounds and isolate an electron-like signal to high precision.

A signal for oscillations due to sterile neutrinos will still be resting on top of a beam intrinsic backgrounds.

Beam intrinsic backgrounds can be constrained by using $\nu_\mu$ channel.

\[ \pi^+ \rightarrow \mu^+ + \nu_\mu \]

\[ \downarrow \]

\[ \mu^+ \rightarrow e^+ + \bar{\nu}_\mu + \nu_e \]
$\nu_e$ Appearance Oscillation Sensitivity

Statistical Uncertainty Limit for 6.6e20 POT exposure
For any signal in a $\nu_e$ appearance search to be interpreted as an oscillation a disappearance signal with an equal or greater probability must also be observed.

When using only a single detector, large uncertainties (~15-20%) in the absolute event rate are expected.

This search is feasible only with multiple LArTPCs at different baselines.
\( \nu_\mu \) Disappearance Oscillation Sensitivity

**Statistical and Flux Uncertainty Limit for 6.6e20 POT exposure**

- LAr1-ND (100m)
- MicroBooNE (470m)
- T600 (600m)

\[ \Delta m^2_{41} \]
Outlook

MicroBooNE will begin data taking later this year providing us a dedicated look at the MiniBooNE excess

The SBN program will provide a definitive statement about whether the short baseline anomalies come from sterile neutrino oscillations

Discovering any number of sterile neutrinos would be revolutionary!
LArTPC Timeline: Towards LBNF

Baseline (m)

SBN

LBNF

Time

2012  2014  2016  2020  2030
Backup Slides
Neutrino Mixing Matrix: PMNS

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

smaller $\nu_e$ content
$|U_{e1}|^2 > |U_{e2}|^2 > |U_{e3}|^2$

KamLAND wiggles $|U_{e1}|^2$
SNO CC KamLAND $|U_{e2}|^2$
Reactor/LBL $|U_{e3}|^2(1 - |U_{e3}|^2)$

SNO NC $|U_{e2}|^2 + |U_{\mu2}|^2 + |U_{\tau2}|^2$
SK & OPERA Tau's $|U_{\tau3}|^2$
Atm Nus/LBL $|U_{\mu3}|^2(1 - |U_{\mu3}|^2)$

little Information!
BNB Flux

Flux from BNB in nu mode at LAr1-ND (100m)

Flux from BNB in nu mode at MicroBooNE (470m)
LArTPC vs. Water Cherenkov

(Cherenkov Detector)

π^0 \rightarrow \gamma + \gamma

(LArTPC)
LSND: Liquid Scintillator Neutrino Detector

800 MeV proton beam from LANSCE accelerator

Water target
Copper beamstop

LSND Detector
<table>
<thead>
<tr>
<th></th>
<th>He</th>
<th>Ne</th>
<th>Ar</th>
<th>Kr</th>
<th>Xe</th>
<th>Water</th>
</tr>
</thead>
<tbody>
<tr>
<td>Boiling Point [K] @ 1atm</td>
<td>4.2</td>
<td>27.1</td>
<td>87.3</td>
<td>120.0</td>
<td>165.0</td>
<td>373</td>
</tr>
<tr>
<td>Density [g/cm³]</td>
<td>0.125</td>
<td>1.2</td>
<td>1.4</td>
<td>2.4</td>
<td>3.0</td>
<td>1</td>
</tr>
<tr>
<td>Radiation Length [cm]</td>
<td>755.2</td>
<td>24.0</td>
<td>14.0</td>
<td>4.9</td>
<td>2.8</td>
<td>36.1</td>
</tr>
<tr>
<td>Scintillation [γ/MeV]</td>
<td>19,000</td>
<td>30,000</td>
<td>40,000</td>
<td>25,000</td>
<td>42,000</td>
<td></td>
</tr>
<tr>
<td>dE/dx [MeV/cm]</td>
<td>0.24</td>
<td>1.4</td>
<td>2.1</td>
<td>3.0</td>
<td>3.8</td>
<td>1.9</td>
</tr>
<tr>
<td>Scintillation λ [nm]</td>
<td>80</td>
<td>78</td>
<td>128</td>
<td>150</td>
<td>175</td>
<td></td>
</tr>
</tbody>
</table>
Muon vs. Pion, ArgoNeut Data

ArgoNeut Data

ArgoNeut Data

Low charge

High charge
Neutral Current (NC) events containing a charged pion form a background for this analysis since the pion ionization energy loss is the same as for muons.
An advanced BNB simulation, based on dedicated hadron production data, will allow detailed study of the correlations between near and far fluxes which will allow us to optimize the near detector location.

Here we show the impact of a 3% uncorrelated systematic uncertainty as an example.