Accelerator-Based Neutrino Oscillation Experiments

Outline

- Basics
- Early experiments
- CHORUS / NOMAD
- LSND / KARMEN / MiniBooNE
- K2K / MINOS / Gran Sasso
- Neutrino Factories
Neutrinos are produced by the weak interaction in weak interaction eigenstates: $\nu_e, \nu_\mu, \nu_\tau$

There is no reason for these eigenstates to be identical to the mass eigenstates: $\nu_1, \nu_2, \nu_3$

They are related by a unitary transformation:

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

This has come to be known as the Maki-Nakagawa-Sakata matrix after the physicists who in 1962 first wrote down a Cabibbo-like matrix for neutrinos.
Basics: Two $\nu$ Oscillations

- The mass eigenstates propagate as $e^{-iEt/\hbar}$. Thus, different masses develop different phases with time, resulting in oscillations in the weak eigenstates:
- If we consider only 2 states, then

$$\nu_\alpha = \nu_1 \cos \theta + \nu_2 \sin \theta$$
$$\nu_\beta = -\nu_1 \sin \theta + \nu_2 \cos \theta$$

and

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

where

$$\Delta m^2 \equiv (m_1^2 - m_2^2) \text{ is in (eV} / c^2)^2, L \text{ is in km, and } E \text{ is in GeV.}$$
Basics: $L/E$ Dependence

- In this case there are only two parameters to be measured: $\sin^2(2\theta)$, which determines the size of the oscillation, and $\Delta m^2$ in $\sin^2(1.27 \Delta m^2 L/E)$, which determines the dependence of the oscillation on $L/E$.

- For $\Delta m^2 \ll L/E$, $P \rightarrow \sin^2(2\theta)(1.27 \Delta m^2 L/E)^2$

- For $\Delta m^2 \gg L/E$, $P \rightarrow \sin^2(2\theta)(1/2)$

- Maximum sensitivity to both parameters at $E/L \approx 0.81 \Delta m^2$
Basics: Types of Experiments

- Disappearance or appearance
  - Disappearance: Sum of all oscillations including those to sterile neutrinos
  - Appearance: Specific channel, in general capable of greater sensitivity to \( \sin^2(2\theta) \)

- One or Two detectors
  - One detector: Expectations must be calculated
  - Two detectors: Expectations taken from near detector. No disadvantages.
Basics: Exclusion Plots

1981 Fermilab Bubble Chamber Experiment

$\nu_\mu \to \nu_e$

$P \propto \sin^2(2\theta)$

Allowed

Excluded 90% c.l.

Maximum sensitivity

$P \propto \sin^2(2\theta)(\Delta m^2)^2$

1983 CERN 2 Detector Counter Experiment

$\nu_\mu \to \nu_\chi$

Both detectors see oscillations

Allowed

Excluded 90% c.l.
Increasingly, we need to consider 3 neutrino mixing.

A 3x3 unitary matrix has 4 independent parameters, three angles and a complex phase. We take these to be $\theta_{12}, \theta_{13}, \theta_{23}$ and $\delta$. Then

$$
\begin{pmatrix}
\nu_e \\
\nu_\mu \\
\nu_\tau
\end{pmatrix} =
\begin{pmatrix}
 c_{12} c_{13} & s_{12} c_{13} & s_{13} e^{-i\delta} \\
-s_{12} c_{23} - c_{12} s_{23} s_{13} e^{i\delta} & c_{12} c_{23} - s_{12} s_{23} s_{13} e^{i\delta} & s_{23} c_{13} \\
 s_{12} s_{23} - c_{12} c_{23} s_{13} e^{i\delta} & -c_{12} s_{23} - s_{12} c_{23} s_{13} e^{i\delta} & c_{23} c_{13}
\end{pmatrix}
\begin{pmatrix}
\nu_1 \\
\nu_2 \\
\nu_3
\end{pmatrix}
$$

where $c_{ij} \equiv \cos(\theta_{ij})$ and $s_{ij} \equiv \sin(\theta_{ij})$. 
With 3 neutrinos, a CP violation term enters, but it will not be important in our discussion until we discuss neutrino factories.

\[ P(\nu_\alpha \rightarrow \nu_\beta) = P_{CP^+}(\nu_\alpha \rightarrow \nu_\beta) + P_{CP^-}(\nu_\alpha \rightarrow \nu_\beta), \text{ where} \]

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

\[ P_{CP^-}(\nu_\alpha \rightarrow \nu_\beta) = 2 \sum_{i < j} \text{Im}(U_{\alpha i}^* U_{\beta i}^* U_{\alpha j} U_{\beta j}) \sin \left( \frac{2.54 \Delta m_{ij}^2 L}{E} \right), \text{ where} \]

\[ \Delta m_{ij}^2 \equiv (m_i^2 - m_j^2) \text{ is in (eV / c}^2)\text{, L is in km, and E is in GeV.} \]

**N.B.:** \[ P(\nu_\alpha \rightarrow \nu_\beta) = P(\bar{\nu}_\beta \rightarrow \bar{\nu}_\alpha) = P_{CP^+}(\nu_\alpha \rightarrow \nu_\beta) + P_{CP^-}(\nu_\alpha \rightarrow \nu_\beta) \]

\[ \text{and} \ P(\bar{\nu}_\alpha \rightarrow \bar{\nu}_\beta) = P(\nu_\beta \rightarrow \nu_\alpha) = P_{CP^+}(\nu_\alpha \rightarrow \nu_\beta) - P_{CP^-}(\nu_\alpha \rightarrow \nu_\beta) \]
Why Accelerator Experiments?

<table>
<thead>
<tr>
<th>Source</th>
<th>Neutrino types</th>
<th>Mode</th>
<th>Advantage</th>
</tr>
</thead>
<tbody>
<tr>
<td>Solar</td>
<td>( \nu_e )</td>
<td>Disappearance</td>
<td>Great distance</td>
</tr>
<tr>
<td>Atmospheric</td>
<td>Mixture of ( \nu_e, \bar{\nu}<em>e, \nu</em>\mu, \bar{\nu}_\mu )</td>
<td>Mostly disappearance</td>
<td>Variable distance</td>
</tr>
<tr>
<td>Reactor</td>
<td>( \bar{\nu}_e )</td>
<td>Disappearance</td>
<td>Low energy</td>
</tr>
<tr>
<td>Accelerator</td>
<td>Mostly ( \nu_\mu )</td>
<td>Either</td>
<td>Control of energy and baseline</td>
</tr>
<tr>
<td>( \pi^+/K^+ )</td>
<td>( \nu_\mu ) and ( \bar{\nu}_e )</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Accelerator</td>
<td>( \mu^- )</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Gary Feldman       SLAC Summer Institute       14 - 25 August 2000
Where Do We Stand?

- Solar favored solution (LMA):
  - $2 \times 10^{-5} < \Delta m^2 < 10^{-4} \text{ (eV} / \text{c}^2\text{)}^2$
  - $\sin^2(2\theta) > 0.6$
  - Sterile neutrino disfavored at 95% c.l.

- Atmospheric favored solution:
  - $1.5 \times 10^{-3} < \Delta m^2 < 5 \times 10^{-3} \text{ (eV} / \text{c}^2\text{)}^2$
  - $\sin^2(2\theta) > 0.9$
  - $\nu_\mu \rightarrow \nu_\tau$ favored at 99% c.l.

- LSND experiment
  - $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ oscillation with $\Delta m^2 > 0.2 \text{ (eV} / \text{c}^2\text{)}^2$

- All three of these results cannot be correct!
The first accelerators with intense enough beams to create neutrino beams were the CERN PS (1959) and the Brookhaven AGS (1960).

In 1962, L. Lederman, M. Schwartz, and J. Steinberger, et al. Perform the first accelerator neutrino experiment at the AGS.
The First Accelerator Neutrino Experiment

- 34 single muon events, 5 consistent with cosmic ray background
- 6 “shower” events, consistent with neutron, misidentified muon, and beam $\nu_e$ backgrounds
- Experimenter’s conclusion: There are two types of neutrinos. (The possibility of neutrino oscillations suggested by Pontecorvo 5 years later in 1967.)
- Average $E_\nu \sim 1$ GeV; average $L \sim 24$ m
- We would say today that the experiment excluded $\nu_\mu \rightarrow \nu_e$ oscillations at the 90% c.l. for
  - $\Delta m^2 > 15 \text{ (eV/c}^2)^2$ for $\sin^2(2\theta) = 1$
  - $\sin^2(2\theta) > 0.4$ for high $\Delta m^2$
Early Experiments

- First round of dedicated neutrino oscillation experiments were done in the 1980’s.

- Three types:
  - $\nu_\mu$ disappearance
  - First two-detector experiments
  - $\nu_\mu \rightarrow \nu_e$ appearance
  - $\nu_\mu \rightarrow \nu_\tau$ appearance
Early Experiments: CCFR $\nu_\mu$ Disappearance

- Detectors at 700 and 1100 m

108 T scintillators every 10 cm
chambers every 30 cm

444 T (fiducial)
scintillators every 10 cm
chambers every 20 cm
Early Experiments:
CCFR $\nu_\mu$ Disappearance

- Typical coarse detector
Early Experiments: CCFR $\nu_\mu$ Disappearance

- Dichromatic beam at 100, 140, 165, 200 and 250 GeV/c $\pi$ and K
Early Experiments: CCFR $\nu_\mu$ Disappearance

- Dichromatic radius vs. energy

$\pi \rightarrow \mu \nu$ and $K \rightarrow \mu \nu$ are 2-body decays, so angle and energy are completely correlated.

Energy was determined from the radius!
Early Experiments: CCFR $\nu_{\mu}$ Disappearance

- Corrections and results

Monte Carlo corrections typically 3%
Early Experiments: CCFR $\nu_\mu$ Disappearance

- Exclusion plot

![Exclusion plot graph]
Early Experiments: CDHS and CHARM $\nu_\mu$ Disappearance

- CERN low energy $\nu$ beam (19.2 GeV $p$)
  - Detectors at 130 m and 900 m
  - Bare target beam with average $E = 3$ GeV
Early Experiments: CDHS $\nu_\mu$ Disappearance

**Detectors:**

100 T Near Detector

600 T Far Detector

Type I: 2.5 cm Fe  
Type II: 5 cm Fe  
Type III: 15 cm Fe
Early Experiments: CDHS $\nu_\mu$ Disappearance

- **Corrections:**
  - Bare target to get approximate $L^{-2}$ scaling
  - Event length used to estimate energy
  - Remaining corrections 5% or less

![Graph showing energy scaling vs. event length]
Early Experiments: CDHS $\nu_\mu$ Disappearance

**Results**

![Graph showing results of early experiments involving CDHS $\nu_\mu$ disapparence, with data points indicating Type I and Type II modules.](image-url)
Early Experiments:
$\nu_\mu$ Disappearance

**Exclusion plot**

Due to systematic effects, it is difficult to do much better than this in $\sin^2(2\theta)$. 

Gary Feldman  SLAC Summer Institute  14 - 25 August 2000
Early Experiments: \( \nu_\mu \rightarrow \nu_e \) Appearance

- Many neutrino experiments in the 1980s looked for excess electrons in their data samples.
- Backgrounds from
  - \( \nu_e \)s in the beam from \( K_{e3} \) and \( \mu \) decays (usually about 1%)
  - Misidentified electrons from \( \pi_0 \) photons and charged pions
Early Experiments: BNL E776 $\nu_\mu \rightarrow \nu_e$ Appearance

- Most sensitive experiment was Brookhaven E-776
  - Detector 1 km from the target. (Proposed as a two detector experiment, the near detector and half the far detector were not funded.)
  - Wide band beam focused with a magnetic horn
    - Typical $E_\nu = 1.4$ GeV
Early Experiments: BNL E776 Detector

- Detector was a finely segmented EM calorimeter and a muon spectrometer. The EM calorimeter was 230 T of 1 in concrete plates interleaved with proportional drift tubes and scintillators.
Early Experiments: BNL E776 $\nu_\mu \rightarrow \nu_e$ Appearance

- Results (2 months of running in 1986)
  - 136 $e^-$ like events with $131 \pm 30$ background expected
  - 47 $e^+$ like events with $62 \pm 18$ background expected
  - Excluded at 90% c.l.

$$\Delta m^2 > 0.075 \text{ (eV} / c^2)^2$$
for $\sin^2(2\theta) = 1$

$$\sin^2(2\theta) > 0.003$$
for high $\Delta m^2$
Early Experiments: $
u_{\mu} \rightarrow \nu_{\tau}$ Appearance

**Considerations**

- **Indirect:** If $\nu_{\mu}$ disappears and $\nu_e$ does not appear and neutral currents are normal, then $\nu_{\mu} \rightarrow \nu_{\tau}$.
  
  **Limitation:** Cannot probe small $\sin^2(2\theta)$.

- **Direct:** Observe $\nu_{\tau}$ through $\nu_{\tau} N \rightarrow \tau X$.
  
  **Limitation:** Must have $E_\nu$ well above $\tau$ threshold.
  (Threshold is at 3.5 GeV, but $E_\nu$ must be in the 10-20 GeV range to produce substantial numbers of $\tau$s due to threshold effects.)

- **Simplest direct method is to take a picture of the $\tau$!**
Early Experiments:
FNAL E531 $\nu_\mu \rightarrow \nu_\tau$ Appearance

- Detector is an average of 750 m from the neutrino production point

91 kg of emulsion
**Analysis**

- Look for short tracks with kinks
  - 104 events with $p_t > 125$ MeV/c (suppress scattering)
  - 25 events with negative particle (suppress charm)
  - 3 events without muon (suppress charm)
  - 0 events with $p > 2.5$ GeV/c (95% of $\tau$s have this)

*A charmed particle in the emulsion*
Early Experiments:
FNAL E531 $\nu_\mu \rightarrow \nu_\tau$ Appearance

- Exclusion at 90% c.l.

$$\Delta m^2 > 0.9 \text{ (eV} / c^2)^2$$

for $\sin^2(2\theta) = 1$

$$\sin^2(2\theta) > 0.005$$

for high $\Delta m^2$
Early Experiments: Summary

\[ \Delta m^2 (eV^2) \]

\[ \sin^2(2\theta) \]
The search for $\nu_\mu \rightarrow \nu_\tau$ oscillations in the $\Delta m^2$ range of 10 to 1000 (eV/c$^2$)$^2$ became particularly attractive in the early 1990’s due to

- COBE results on the anisotropy of the cosmic microwave background coupled with measurements on the clustering of galaxies, which seemed to require hot dark matter.

- Numerology associated with the seesaw mechanism:

$$m(\nu_\alpha) = \left(\frac{m^f_\alpha}{\mathcal{M}}\right)^2 \Rightarrow m(\nu_\tau) = \left(\frac{m(t)}{m(c)}\right)^2$$

which gives $\nu_\tau$ masses in this range if the $\nu_\mu$ mass is associated with solar matter oscillations.
Two CERN experiments, CHORUS and NOMAD, had the goal of increasing the sensitivity in $\sin^2(2\theta)$ by an order of magnitude over what had been achieved by E531.

CHORUS used the “traditional” method of taking a picture of the $\nu_\tau$'s in emulsion. Same basic design as E531, but with 770 kg of emulsion.

NOMAD sought to identify $\nu_\tau$'s solely by kinematic criteria.

Both experiments in the CERN 450 GeV SpS beam about 600 m from the average decay point.
Average $\nu_\mu$ energy = 24 GeV

Average $\bar{\nu}_\mu$ interaction energy = 43 GeV
## CHORUS Scanning

<table>
<thead>
<tr>
<th></th>
<th>$1 \mu$</th>
<th>$0 \mu$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Events scanned</td>
<td>355 k</td>
<td>85 k</td>
</tr>
<tr>
<td>Vertices located</td>
<td>144 k</td>
<td>20 k</td>
</tr>
<tr>
<td>Events selected for eye-scan</td>
<td>11 k</td>
<td>2 k</td>
</tr>
<tr>
<td>Kink candidates after eye-scan</td>
<td>0</td>
<td>0</td>
</tr>
</tbody>
</table>
CHORUS Manual Scanning

- Low momentum background track: ~78%
- Parent=Daughter, No angle difference: ~5%
- Backward-going nuclear fragment: ~13%
- Hadron interaction: ~3%
- Decay (Kink): ~1%

\[ P_t > 250 \text{ MeV/c to eliminate } \pi/K \text{ decays reduces this to 0 } \]
<table>
<thead>
<tr>
<th>Background</th>
<th>$1\mu$</th>
<th>$0\mu$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Charm from $\bar{\nu}$ with missed lepton $\bar{\nu}N \rightarrow D^- X\ell^+$; $D^- \rightarrow \mu^- / h^- +$ neutrals</td>
<td>0.11</td>
<td>0.02</td>
</tr>
<tr>
<td>Charm from $\nu$ with wrong charge</td>
<td>neg</td>
<td>0.3</td>
</tr>
<tr>
<td>Associated charm production in NC</td>
<td>neg</td>
<td>neg</td>
</tr>
<tr>
<td>Hadronic white kinks (scattering with no recoil or nuclear breakup)</td>
<td>neg</td>
<td>0.8</td>
</tr>
<tr>
<td>Prompt beam $\nu_\tau$</td>
<td>neg</td>
<td>neg</td>
</tr>
<tr>
<td><strong>Total background</strong></td>
<td>0.11</td>
<td>1.1</td>
</tr>
</tbody>
</table>
Red and blue curves correspond to different statistical treatments.

With additional scanning, CHORUS expects to reach a sensitivity of $10^{-4}$. 

$\Delta m^2 \text{ (eV/c}^2)^2 \quad \sin^2(2\theta)$