## Evidence For $\nu$ Flavor Change

<table>
<thead>
<tr>
<th>Neutrinos</th>
<th>Evidence of Flavor Change</th>
</tr>
</thead>
<tbody>
<tr>
<td>Solar</td>
<td>Compelling</td>
</tr>
<tr>
<td>Reactor</td>
<td>Compelling</td>
</tr>
<tr>
<td>($L \sim 180$ km)</td>
<td></td>
</tr>
<tr>
<td>Atmospheric</td>
<td>Compelling</td>
</tr>
<tr>
<td>Accelerator</td>
<td>Compelling</td>
</tr>
<tr>
<td>($L = 250$ and $735$ km)</td>
<td></td>
</tr>
<tr>
<td>Stopped $\mu^+$ Decay ($L \approx 30$ m)</td>
<td>Unconfirmed by MiniBooNE</td>
</tr>
</tbody>
</table>
The neutrino flavor-change observations imply that —

Neutrinos have nonzero masses

and that —

Leptons mix.
What We Have Learned
The \((\text{Mass})^2\) Spectrum

\(\nu_3\)

\(\Delta m^2_{\text{atm}}\)

or

\(\nu_2\)

\(\nu_1\)

\(\Delta m^2_{\text{sol}}\)

\(\nu_2\)

\(\nu_1\)

\(\Delta m^2_{\text{atm}}\)

\(\nu_3\)

\(\Delta m^2_{\text{sol}}\)

\(\Delta m^2_{\text{sol}} \approx 7.6 \times 10^{-5} \text{ eV}^2, \quad \Delta m^2_{\text{atm}} \approx 2.4 \times 10^{-3} \text{ eV}^2\)
Are There *More* Than 3 Mass Eigenstates?

When only two neutrinos count,

\[ P(\nu_\alpha \rightarrow \nu_\beta) = \sin^2 2\theta \sin^2 \left[ 1.27\Delta m^2 (eV^2) \frac{L(km)}{E(GeV)} \right] \]

*Rapid* neutrino oscillation reported by LSND —

\[ \Delta m^2_{atm} = 2.4 \times 10^{-3} \text{ eV}^2 \]
\[ \Delta m^2_{sol} = 7.6 \times 10^{-5} \text{ eV}^2 \]

\[ \sim 1 \text{ eV}^2 \]

in contrast to

At least 4 mass eigenstates.
MiniBooNE Search for $\nu_\mu \rightarrow \nu_e$

- **NEW:**
  - this energy bin

- No excess above background for energies $E_\nu > 475$ MeV.
- Unexplained excess for $E_\nu < 475$ MeV.
- Two-neutrino oscillation cannot fit LSND and MiniBooNE.
- We shall assume 3 mass eigenstates (but there may be more).
Leptonic Mixing

This has the consequence that —

\[ |\nu_i> = \sum_\alpha U_{\alpha i} |\nu_\alpha> \]

Flavor-\(\alpha\) fraction of \(\nu_i = |U_{\alpha i}|^2\).

When a \(\nu_i\) interacts and produces a charged lepton, the probability that this charged lepton will be of flavor \(\alpha\) is \(|U_{\alpha i}|^2\).
The spectrum, showing its approximate flavor content, is

$\nu_1 \rightarrow \nu_2 \rightarrow \nu_3$

Normal

$\Delta m^2_{\text{atm}}$ $\nu_1 \rightarrow \nu_2 \rightarrow \nu_3$

Inverted

$\Delta m^2_{\text{sol}}$

$\Delta m^2_{\text{sol}}$

$\sin^2 \theta_{13}$

$\sin^2 \theta_{13}$

$\nu_e [|U_{ei}|^2]$ $\nu_\mu [|U_{\mu i}|^2]$ $\nu_\tau [|U_{\tau i}|^2]$
The Mixing Matrix

\[
U = \begin{bmatrix}
1 & 0 & 0 \\
0 & c_{23} & s_{23} \\
0 & -s_{23} & c_{23}
\end{bmatrix}
\times
\begin{bmatrix}
c_{13} & 0 & s_{13} e^{-i \delta} \\
0 & 1 & 0 \\
-s_{13} e^{i \delta} & 0 & c_{13}
\end{bmatrix}
\times
\begin{bmatrix}
c_{12} & s_{12} & 0 \\
-s_{12} & c_{12} & 0 \\
0 & 0 & 1
\end{bmatrix}
\times
\begin{bmatrix}
e^{i \alpha_1 / 2} & 0 & 0 \\
0 & e^{i \alpha_2 / 2} & 0 \\
0 & 0 & 1
\end{bmatrix}
\]

\[c_{ij} \equiv \cos \theta_{ij}\]
\[s_{ij} \equiv \sin \theta_{ij}\]

\[\theta_{12} \approx \theta_{\text{sol}} \approx 35^\circ, \quad \theta_{23} \approx \theta_{\text{atm}} \approx 37-53^\circ, \quad \theta_{13} \lesssim 10^\circ\]

\[\delta \text{ would lead to } P(\bar{\nu}_\alpha \rightarrow \bar{\nu}_\beta) \neq P(\nu_\alpha \rightarrow \nu_\beta).\]

But note the crucial role of \[s_{13} \equiv \sin \theta_{13}.\]
“Atmospheric” $\Delta m^2$ and mixing angle from MINOS, Super-K, and K2K.

From talk by N. Saoulidou
“Solar” $\Delta m^2$ and mixing angle from KamLAND and SNO.

From K. Heeger at TAUP 2007
7Be Solar Neutrinos

Until recently, only the $^8$B solar neutrinos, with $E \sim 7$ MeV, had been studied in detail.

The Large Mixing Angle MSW (matter) effect boosts the fraction of the $^8$B solar $\nu_e$ that get transformed into neutrinos of other flavors to roughly 70%.

At the energy $E = 0.862$ MeV of the $^7$Be solar neutrinos, the matter effect is expected to be very small. Only about 45% of the $^7$Be solar $\nu_e$ are expected to change into neutrinos of other flavors.
Borexino —

Detects the $^7\text{Be}$ solar neutrinos via $\nu_e \rightarrow \nu_e$ elastic scattering.

**Event rate (Counts/day/100 tons)**

- Observed: $47 \pm 7\text{ (stat)} \pm 12\text{ (syst)}$
- Expected (No Osc): $75 \pm 4$
- Expected (With 45% Osc): $49 \pm 4$
- Expected (With 70% Osc): $\sim 31$
The Open Questions
• What is the absolute scale of neutrino mass?

• Are neutrinos their own antiparticles?

• Are there “sterile” neutrinos?

We must be alert to surprises!
• What is the pattern of mixing among the different types of neutrinos?

What is $\theta_{13}$?

• Is the spectrum like $\equiv$ or $\equiv$?

• Do neutrino – matter interactions violate CP?

Is $P(\bar{\nu}_\alpha \rightarrow \bar{\nu}_\beta) \neq P(\nu_\alpha \rightarrow \nu_\beta)$?
• What can neutrinos and the universe tell us about one another?

• Is CP violation involving neutrinos the key to understanding the matter–antimatter asymmetry of the universe?

• What physics is behind neutrino mass?
The Importance of Some Questions, and How They May Be Answered
That is, for each mass eigenstate \( \nu_i \), does —

- \( \bar{\nu}_i = \nu_i \) (Majorana neutrinos)

or

- \( \bar{\nu}_i \neq \nu_i \) (Dirac neutrinos) ?

Equivalently, do neutrinos have \textit{Majorana masses}? If they do, then the mass eigenstates are \textit{Majorana neutrinos}. 
Majorana Masses

Out of, say, a left-handed neutrino field, $\nu_L$, and its charge-conjugate, $\nu_L^c$, we can build a **Majorana** mass term —

$$m_L \bar{\nu}_L^c \nu_L$$

Charge-conjugate fields:

$$\psi_c = \psi(\text{Particle} \leftrightarrow \text{Antiparticle})$$

Manifestly, a **Majorana** mass term does not conserve the Lepton Number $L$ defined by $L(\nu) = L(\ell^-) = -L(\bar{\nu}) = -L(\ell^+) = 1$. 
The objects $\nu_L$ and $\nu_L^c$ in $m_L\nu_L^c\nu_L$ are not the mass eigenstates, but just the neutrinos in terms of which the model is constructed.

$m_L\nu_L^c\nu_L$ induces $\nu_L \leftrightarrow \nu_L^c$ mixing.

As a result of $K^0 \leftrightarrow \bar{K}^0$ mixing, the neutral $K$ mass eigenstates are —

$$K_{S,L} \equiv (K^0 \pm \bar{K}^0)/\sqrt{2} \ . \quad \bar{K}_{S,L} = K_{S,L} \ .$$

As a result of $\nu_L \leftrightarrow \nu_L^c$ mixing, the neutrino mass eigenstate is —

$$\nu_i = \nu_L + \nu_L^c = "\nu + \bar{\nu}" \ . \quad \bar{\nu}_i = \nu_i \ .$$
Why Many Theorists Think Majorana Mass Terms Are Likely

The Standard Model (SM) is defined by the fields it contains, its symmetries (notably Weak Isospin Invariance), and its renormalizability.

Anything allowed by the symmetries occurs in nature.

The SM contains no $\nu$ mass, and no $\nu_R$ field, only $\nu_L$.

Now that we know the neutrino has mass, we must somehow extend the SM to accommodate it. In doing this, we can either add $\nu_R$, or not add it.
If we *do not* add $\nu_R$, then the only neutrino mass term we can construct is $m_L \nu_L^c \nu_L$, a Majorana mass term.

If we *do* add $\nu_R$, then we can construct the Dirac mass term $m_D \bar{\nu}_L \nu_R$. If this term is all there is, the neutrino gets its mass the same way that a quark or charged lepton does. No Majorana neutrino masses.

*However* —

Unlike $\nu_L$, $\nu_R$ carries no Weak Isospin.

Thus, once $\nu_R$ has been added, no SM symmetry prevents the occurrence of the Majorana mass term $m_R \bar{\nu}_R^c \nu_R$. 
If anything allowed by the *extended* SM occurs in nature, then neutrinos have *Majorana masses*. Hence, the neutrino mass eigenstates are their own antiparticles.
To Determine If Neutrinos Are Their Own Antiparticles
The Promising Approach —

Neutrinoless Double Beta Decay \([0\nu\beta\beta]\)

We are looking for a small Majorana neutrino mass. Thus, we will need a lot of parent nuclei (say, one ton of them).
Whatever diagrams cause $0\nu\beta\beta$, its observation would imply the existence of a Majorana mass term:

Schechter and Valle

$(\bar{\nu})_R \rightarrow \nu_L : A$ Majorana mass term

$\therefore \quad 0\nu\beta\beta \rightarrow \bar{\nu}_i = \nu_i$
We anticipate that $0\nu\beta\beta$ is dominated by a diagram with Standard Model vertices:

$$\sum_i U_{ei} \bar{\nu}_i \nu_i W^- W^-$$

Then —

$$\text{Amp}[0\nu\beta\beta] \propto \left| \sum m_i U_{ei}^2 \right| \equiv m_{\beta\beta}$$
How Large is $m_{\beta\beta}$?

How sensitive need an experiment be?

Suppose there are only 3 neutrino mass eigenstates. (More might help.)

Then the spectrum looks like —

Normal hierarchy

Inverted hierarchy
\[
\begin{align*}
&\text{\textbf{Takes 1 ton}} \\
&\text{\(m_{\beta\beta}\) For Each Hierarchy} \\
&\text{\textbf{Takes 100 tons}}
\end{align*}
\]
The Central Role of $\theta_{13}$

Both CP violation and our ability to tell whether the spectrum is normal or inverted depend on $\theta_{13}$.

If $\sin^2 2\theta_{13} > 10^{-(2-3)}$, we can study both of these issues with intense but conventional accelerator $\nu$ and $\bar{\nu}$ beams, produced via

$\pi^+ \rightarrow \mu^+ + \nu_{\mu}$ and $\pi^- \rightarrow \mu^- + \bar{\nu}_{\mu}$.

Determining $\theta_{13}$ is an important step.
How $\theta_{13}$ May Be Measured

*Reactor* neutrino experiments are the cleanest way.

*Accelerator* neutrino experiments can also probe $\theta_{13}$.
Now it is entwined with other parameters.

In addition, accelerator experiments can probe *whether the mass spectrum is normal or inverted*, and look for *CP violation*.

All of this is done by studying $\nu_\mu \rightarrow \nu_e$ and $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ while the beams travel hundreds of kilometers.
The Mass Spectrum: \(\equiv\) or \(\equiv\)?

Generically, grand unified models (GUTS) favor —

—

GUTS relate the Leptons to the Quarks.

— is un-quark-like, and would probably involve a lepton symmetry with no quark analogue.
How To Determine If The Spectrum Is Normal Or Inverted

Exploit the fact that, in matter,

![Diagram](image)

affects $\nu$ and $\bar{\nu}$ oscillation (differently), and leads to —

$$\frac{P(\nu_\mu \rightarrow \nu_e)}{P(\bar{\nu}_\mu \rightarrow \bar{\nu}_e)} \begin{cases} > 1 ; & \text{Note fake CP} \\ < 1 ; & \text{Note dependence on the mass ordering} \end{cases}$$
Q: Does matter still affect $\nu$ and $\bar{\nu}$ differently when $\bar{\nu} = \nu$?

A: Yes!

The weak interactions violate *parity*. Neutrino – matter interactions depend on the neutrino *polarization*.
Do Neutrino Interactions Violate CP?

The observed CP in the weak interactions of quarks cannot explain the Baryon Asymmetry of the universe.

Is leptonic CP, through Leptogenesis, the origin of the Baryon Asymmetry of the universe?

(Fukugita, Yanagida)
A See-Saw Mechanism is proposed as the most popular theory of why neutrinos are so light. In this mechanism, the very heavy neutrinos $N$ would have been made in the hot Big Bang.
The heavy neutrinos \( N \), like the light ones \( \nu \), are Majorana particles. Thus, an \( N \) can decay into \( \ell^- \) or \( \ell^+ \).

*If neutrino oscillation violates CP, then quite likely so does \( N \) decay. In the See-Saw, these two CP violations have a common origin.*

Then, in the early universe, we would have had different rates for the CP-mirror-image decays –

\[
N \to \ell^- + \ldots \quad \text{and} \quad N \to \ell^+ + \ldots
\]

This would have led to unequal numbers of leptons and antileptons (Leptogenesis).

Then, Standard-Model *Sphaleron* processes would have turned \( \sim 1/3 \) of this leptonic asymmetry into a *Baryon Asymmetry*. 
How To Search for $\mathcal{CP}$
In Neutrino Oscillation

Look for $P(\overline{\nu}_\alpha \rightarrow \overline{\nu}_\beta) \neq P(\nu_\alpha \rightarrow \nu_\beta)$
Q: Can CP violation still lead to $P(\bar{\nu}_\mu \rightarrow \bar{\nu}_e) \neq P(\nu_\mu \rightarrow \nu_e)$ when $\bar{\nu} = \nu$?

A: Certainly!
Separating $CP$ From the Matter Effect

Genuine $CP$ and the matter effect both lead to a difference between $\nu$ and $\bar{\nu}$ oscillation.

But genuine $CP$ and the matter effect depend quite differently from each other on $L$ and $E$.

One can disentangle them by making oscillation measurements at different $L$ and/or $E$. 
Accelerator ($\nu$) Oscillation Probabilities

With $\alpha \equiv \Delta m_{21}^2 / \Delta m_{31}^2$, $\Delta \equiv \Delta m_{31}^2 L / 4E$, and $x \equiv \frac{2\sqrt{2}G_F N_e E}{\Delta m_{31}^2}$

$$P[\nu_\mu \rightarrow \nu_e] \approx \sin^2 2\theta_{13} T_1 - \alpha \sin 2\theta_{13} T_2 + \alpha \sin 2\theta_{13} T_3 + \alpha^2 T_4 ;$$

$$T_1 = \sin^2 \theta_{23} \frac{\sin^2[(1-x)\Delta]}{(1-x)^2}, \quad T_2 = \sin \delta \sin 2\theta_{12} \sin 2\theta_{23} \sin \Delta \frac{\sin(x\Delta) \sin[(1-x)\Delta]}{x \frac{(1-x)}{(1-x)}},$$

$$T_3 = \cos \delta \sin 2\theta_{12} \sin 2\theta_{23} \cos \Delta \frac{\sin(x\Delta) \sin[(1-x)\Delta]}{x \frac{(1-x)}{(1-x)}}, \quad T_4 = \cos^2 \theta_{23} \sin^2 2\theta_{12} \frac{\sin^2(x\Delta)}{x^2}$$

$$P[\bar{\nu}_\mu \rightarrow \bar{\nu}_e] = P[\nu_\mu \rightarrow \nu_e] \text{ with } \delta \rightarrow -\delta \text{ and } x \rightarrow -x.$$  

(Cervera et al., Freund, Akhmedov et al.)
Strategies

The matter-effect parameter $x$ has $|x| \approx E/12$ GeV.

At $L/E$ of the 1\textsuperscript{st} “atmospheric” oscillation peak, and $E \sim 1$ GeV, the effect of matter on the neutrino atmospheric oscillation term ($\sin^2 2\theta_{13} T_1$) is —

\[
\frac{1}{(1-x)^2} \approx 1 \pm \left( \frac{E}{6 \text{GeV}} \right)
\]

At fixed $L/E$, genuine CP effects do not change with $E$, but the matter effect grows, enhancing (suppressing) the oscillation if the hierarchy is Normal (Inverted).
If $E \rightarrow E/3$ at fixed $L$, we go from the 1\textsuperscript{st} atmospheric oscillation peak to the 2\textsuperscript{nd} one.

When $E \rightarrow E/3$ at fixed $L$, \textit{CP is tripled, but the matter effect is reduced by a factor of 3}. 
U.S. Plans and Hopes
The Present, and a Part of the Future

American researchers participate in —

**MINOS, MiniBooNE, SciBooNE, and (soon) MINERvA,** in R&D on **EXO and Majorana,**

and, beyond the U.S. border, in —

**KamLAND, SNO, and Super-Kamiokande.**

They will participate in **NOvA,** and, offshore, in —

**Cuore, Daya Bay, Double Chooz, and T2K.**
Beyond NO\(\nu\)A

Although it is not certain, it appears quite likely that the U.S. will mount a substantial program of accelerator neutrino experiments beyond NO\(\nu\)A.

The goals include determining whether neutrino oscillation violates CP.

The details of this program are not yet known, but several studies have been carried out:
U.S. Long Baseline Neutrino Study
(Brookhaven & Fermilab)

Explored two approaches:

1. Add detector mass, beyond NOvA, in Fermilab’s NuMI beamline

2. Build at Fermilab a new, wide-band beam aimed at a very large ($\nu$ and p-decay) detector more than 1000 km away, possibly in a Deep Underground Science and Engineering Laboratory (DUSEL)

The 2nd approach has greater physics reach, particularly for determining whether the spectrum is Normal or Inverted, and greater cost.
Fermilab Steering Group

Fermilab’s top priority is to bid to host the International Linear Collider (ILC).

But it is recognized that even if the ILC comes to Fermilab, it may not be taking data before ~ 2025.

What would be the best scientific program for Fermilab until then?
ILC Decision Timelines

Possible ILC Decision Timelines

- LHC discoveries
- US colliders Shutdown
- Great Opportunity for ILC
- International Agreements
- Site selected

2010 ILC Decision

EPP2010 & P5 Assumption

ILC RDR with Cost Estimate in Feb. 2007

(Young-Kee Kim)
If ILC remains near the proposed timeline, the Fermilab neutrino program will focus on $NO_{\nu}A$ and several small experiments.

If ILC start is delayed a couple of years, Fermilab should undertake $S\!N\!u\!M\!I$, an upgrade of the NuMI beamline.

If ILC postponement would accommodate an interim major project, the laboratory should undertake $Project \, X$, an ILC-related high-intensity proton source.
Project X: Properties

~2.3 MW at 120 GeV for Neutrino Science
Initially NOvA, Possibly DUSEL later

200 kW at 8 GeV for Precision Physics

8 GeV H⁻ Linac with ILC Beam Parameters
(9mA x 1msec x 5Hz)

\( v < c \) \quad v = c \) (ILC Linac)
Project X: Proton Beam Power

\[ \text{(Young-Kee Kim)} \]

with Main Injector Upgrade

Inject into
Main Injector

\[ \begin{align*}
\text{sNuMI} \\
\text{NuMI (NOvA)} \\
\text{NuMI (MINOS)}
\end{align*} \]
Mass Ordering and CP Reach of Project X

Discovery Potential $\text{sign} \Delta m^2_{31}$

- CHOZ Excluded

- Project X with 2 detectors

- Project X with longer baseline detector

3 $\sigma$ Discovery Potential for $\delta \neq 0$ and ($\neq \pi$)

- CHOZ Excluded

- Project X with 2 detectors

- Project X with longer baseline detector
Summary

We have learned a lot about the neutrinos in the last decade.

What we have learned raises some very interesting questions.

Prospects for answering them are bright.