The Big Picture

Boris Kayser, INT, August 2, 2010
The $(\text{Mass})^2$ Spectrum

Normal

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

Inverted

Are there more mass eigenstates, as LSND suggests, and MiniBooNE recently hints?
The Absolute Scale of Neutrino Mass

How far above zero is the whole pattern?

Oscillation Data $\Rightarrow \sqrt{\Delta m^2_{\text{atm}}} < \text{Mass}[\text{Heaviest } \nu_i]$
The Upper Bound From Cosmology

Neutrino mass affects large scale structure.

Cosmological Data + Cosmological Assumptions $\Rightarrow$

\[ \sum m_i < (0.17 - 1.0) \text{ eV}. \]

If there are only 3 neutrinos,

\[ 0.04 \text{ eV} \leq \text{Mass}[\text{Heaviest } \nu_i] < (0.07 - 0.4) \text{ eV} \]

Seljak, Slosar, McDonald
Hannestad; Pastor

\[ \sqrt{\Delta m^2_{\text{atm}}} \]

Cosmology

\[ \text{Mass}(\nu_i) \]
The Upper Bound From Tritium

Cosmology is wonderful, but there are known loopholes in its argument concerning neutrino mass.

The absolute neutrino mass can in principle also be measured by the kinematics of $\beta$ decay.

**Tritium decay:**

$$^{3}H \rightarrow ^{3}He + e^{-} + \bar{\nu}_{i}; \; i = 1, 2, \text{or} \; 3$$

$$BR\left(^{3}H \rightarrow ^{3}He + e^{-} + \bar{\nu}_{i}\right) \propto |U_{ei}|^{2}$$

In $^{3}H \rightarrow ^{3}He + e^{-} + \bar{\nu}_{i}$, the bigger $m_{i}$ is, the smaller the maximum electron energy is.

*There are 3 separate thresholds in the $\beta$ energy spectrum.*
The $\beta$ energy spectrum is modified according to —

$$(E_0 - E)^2 \Theta[E_0 - E] \Rightarrow \sum |U_{ei}|^2 (E_0 - E) \sqrt{(E_0 - E)^2 - m_i^2} \Theta[(E_0 - m_i) - E]$$

Maximum $\beta$ energy when there is no neutrino mass

Present experimental energy resolution is insufficient to separate the thresholds.

Measurements of the spectrum bound the average neutrino mass —

$$\langle m_\beta \rangle = \sqrt{\sum_i |U_{ei}|^2 m_i^2}$$

Presently: $\langle m_\beta \rangle < 2$ eV

Mainz & Troitzk
Improved $\beta$ energy resolution requires a **BIG** $\beta$ spectrometer.

**KATRIN**

5σ signal if $m_i > 0.35$ eV

Leopoldshafen, 25.11.06
Leptonic Mixing

The neutrinos $\nu_{e, \mu, \tau}$ of definite flavor

$(W \rightarrow e\nu_e$ or $\mu\nu_\mu$ or $\tau\nu_\tau)$

are superpositions of the neutrinos of definite mass:

$$|\nu_\alpha> = \sum_i U^*_{\alpha i} |\nu_i> .$$

Neutrino of flavor

$\alpha = e, \mu, \text{or } \tau$

Neutrino of definite mass $m_i$

Unitary (?) PMNS Leptonic Mixing Matrix
Inverting —

Mass eigenstate $|\nu_i> = \sum_\alpha U_{\alpha i} |\nu_\alpha>$.  

<table>
<thead>
<tr>
<th>$\nu_i$</th>
<th>$\nu_\alpha$</th>
<th>$U_{\alpha i}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>e, µ, τ</td>
<td>PMNS Leptonic Mixing Matrix</td>
<td>Flavor eigenstate</td>
</tr>
</tbody>
</table>

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 $|U_{\alpha i}|^2$.  

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The spectrum, showing its approximate flavor content, is

\[ \sin^2 \theta_{13} \]

(Mass)\(^2\)

\[ \nu_3 \]

\[ \nu_2 \]

\[ \nu_1 \]

or

\[ \sin^2 \theta_{13} \]

\[ \nu_3 \]

\[ \nu_2 \]

\[ \nu_1 \]

Normal

Inverted

\[ \nu_e [\mid U_{ei} \mid^2] \]

\[ \nu_\mu [\mid U_{\mu i} \mid^2] \]

\[ \nu_\tau [\mid U_{\tau i} \mid^2] \]
The Mixing Matrix

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

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

\[\theta_{12} \approx \theta_{\text{sol}} \approx 34^\circ, \quad \theta_{23} \approx \theta_{\text{atm}} \approx 39-51^\circ, \quad \theta_{13} \lesssim 11^\circ\]

\[\delta\] would lead to \(P(\overline{\nu}_\alpha \rightarrow \overline{\nu}_\beta) \neq P(\nu_\alpha \rightarrow \nu_\beta).\) \(\mathbf{\not{CP}}\)

But note the crucial role of \(s_{13} \equiv \sin \theta_{13}.\)
Multiplied out, the mixing matrix is close to the simple **Tri-Bi-Maximal** mixing:

\[
U_{TBM} = \begin{pmatrix}
\sqrt{2}/3 & \sqrt{1}/3 & 0 \\
\sqrt{1}/\sqrt{6} & 1/\sqrt{3} & 1/\sqrt{2} \\
\sqrt{1}/\sqrt{6} & -1/\sqrt{3} & 1/\sqrt{2}
\end{pmatrix}
\]

*Is there a deep underlying reason, such as a symmetry, for this pattern?*
Bounded by reactor exps. with $L \sim 1$ km

From max. atm. mixing, $\nu_3 \approx \frac{\nu_\mu + \nu_\tau}{\sqrt{2}}$

\[ \nu_3 \]

\[ \Delta m^2_{\text{atm}} \]

\{ From $\nu_\mu$ (Up) oscillate but $\nu_\mu$ (Down) don’t \}

\{ In LMA–MSW, $P_{\text{sol}}(\nu_e \rightarrow \nu_e)$ \}

\{ = $\nu_e$ fraction of $\nu_2$ \}

\[ \Delta m^2_{\text{sol}} \]

From distortion of $\overline{\nu_e}$ (reactor) and $\nu_e$ (solar) spectra

\{ From max. atm. mixing, $\nu_1 + \nu_2$ \}

\{ includes $(\nu_\mu - \nu_\tau)/\sqrt{2}$ \}

\[ (\text{Mass})^2 \]

$\nu_e [\mid U_{ei} \mid^2]$  $\nu_\mu [\mid U_{\mu i} \mid^2]$  $\nu_\tau [\mid U_{\tau i} \mid^2]$
The Open Questions
L(S)B  \equiv  A \text{ question for Long (Short) Baselines}

\begin{itemize}
  \item What is the absolute scale of neutrino mass?
  \item Are neutrinos their own antiparticles?
  \item Are there \textit{more} than 3 mass eigenstates?
  \item Are there “sterile” neutrinos?
  \item What are the neutrino magnetic and electric dipole moments?
\end{itemize}
• What is $\theta_{13}$?
How close to maximal is $\theta_{23}$?

• 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?

• What surprises are in store?
Importance, Approaches, and Timelines
Mixing, Mass Ordering, and CP

The Questions For Oscillation Experiments
An approach to neutrino oscillations with entanglement confirms the standard results.
For a neutrino beam of energy $E$, the usual expression for the wavelength $\lambda$ of the oscillation caused by a splitting $\Delta m^2$ is

$$\lambda \equiv \text{Source to Detector distance for one oscillation} = \frac{4\pi E}{\Delta m^2}.$$ 

A recent approach involves entanglement between the neutrino and its associated recoil — the muon in $\pi \rightarrow \mu \nu$. 

The wavelength $\lambda_S$ obtained by this approach looks very different from the usual one.
The wavelength $\lambda_S$ derived by this approach is for oscillation as a function of the lab-frame $\nu - \mu$ separation $S$ at the time in the $\pi$ rest frame when the neutrino is detected.
One finds that —

\[
\frac{\lambda_S}{\lambda_{Usual}} = \frac{S}{L}
\]

That is, the “new” wavelength \( \lambda_S \) is physically equivalent to the usual one.

It just refers to a different distance variable.

B. K., Kopp, Robertson, and Vogel
Two Program Goals

Try to optimize strategy, as a function of $\theta_{13}$, for determining the mass ordering and observing $\mathcal{CP}$.

Emphasize the need to be alert for surprises, and give some examples of possible surprises.
The Mass Spectrum: $\equiv$ or $\equiv$? Why Is This Interesting?

Generically, grand unified models (GUTS) favor —

—

GUTS relate the Leptons to the Quarks.

However, *Majorana masses*, with no quark analogues, could turn $\equiv$ into $\equiv$. 
Why Is $\mathcal{CP}$ In Neutrino Oscillation Interesting?

We are looking for a CP-violating scenario adequate to explain the baryon-antibaryon asymmetry of the universe.

The candidate scenario: \textit{Leptogenesis}.  
\textit{(Fukugita, Yanagida)}
Leptogenesis – The General Idea

Leptogenesis is an outgrowth of the most popular theory of why neutrinos are so light —

The See-Saw Mechanism

Very heavy neutrino \{ \rightarrow N \}

Familiar light neutrino

\{ Yanagida; Gell-Mann, Ramond, Slansky; Mohapatra, Senjanovic; Minkowski \}

The very heavy neutrinos N would have been made in the hot Big Bang.
**Leptogenesis — Step 1**

The heavy neutrinos N, like the light ones ν, are Majorana particles. Thus, an N can decay into $e^-$ or $e^+$.  

*If ν oscillation violates CP, then quite likely so does N decay. In the See-Saw, these two CP violations have a common origin: One Yukawa coupling matrix, y.*

$$\mathcal{L} = y\bar{L}HN$$

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

$$N \rightarrow e^- + H^+ \quad \text{and} \quad N \rightarrow e^+ + H^-$$

*This produces a universe with unequal numbers of leptons and antileptons.*
Leptogenesis — Step 2

The Standard-Model Sphaleron process, which does not conserve Baryon Number $B$, or Lepton Number $L$, but does conserve $B - L$, acts.

There is now a **Baryon Asymmetry**.
Leptogenesis and $\mathcal{CP}$
In Light $\nu$ Oscillation

In a convenient basis, the Yukawa coupling matrix $y$ is the only source of $\mathcal{CP}$ violation among the leptons.

Though $M_D = (\nu y)^\dagger$, the $\mathcal{CP}$ phases in $y$ feed into the leptonic mixing matrix $U$.

$$M_\nu = -U^T \left( M^T_D M_N^{-1} M_D \right) U$$

*Heavy $N$ mass eigenvalues*

*Neutrino Dirac mass matrix*

*Light $\nu$ mass eigenvalues*

*Leptonic mixing matrix*
The Central Role of $\theta_{13}$

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

Determining $\theta_{13}$ is an important step.
Reactor Experiments To Determine $\theta_{13}$

Looking for disappearance of reactor $\overline{\nu}_e$, which have $E \sim 3$ MeV, while they travel $L \sim 1.5$ km is the cleanest way to determine $\theta_{13}$.

\[
P(\overline{\nu}_e \text{ Disappearance}) \equiv \sin^2 2\theta_{13} \sin^2 \left[ 1.27 \Delta m^2_{31} (\text{eV}^2) L(\text{km})/E(\text{GeV}) \right]
\]
Use a near and a far ($L \sim 1.5$ km) detector.
Accelerator Experiments

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 $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$, or their inverses, while the beams travel hundreds or thousands of kilometers.
Accelerator ($\bar{\nu}$) Oscillation Probabilities

With $\alpha \equiv \Delta m^2_{21}/\Delta m^2_{31}$, $\Delta \equiv \frac{\Delta m^2_{31}L}{4E}$, and $x \equiv \frac{2\sqrt{2}G_FN_e E}{\Delta m^2_{31}}$, $m^2(\rightarrow) - m^2(\leftarrow)$

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

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

- CP-odd interference
  $$T_2 = \sin \delta \sin 2\theta_{12} \sin 2\theta_{23} \sin \Delta \frac{\sin(x\Delta)}{x} \frac{\sin[(1-x)\Delta]}{(1-x)},$$

- CP-even interference
  $$T_3 = \cos \delta \sin 2\theta_{12} \sin 2\theta_{23} \cos \Delta \frac{\sin(x\Delta)}{x} \frac{\sin[(1-x)\Delta]}{(1-x)},$$

- Solar
  $$T_4 = \cos^2 \theta_{23} \sin^2 2\theta_{12} \frac{\sin^2(x\Delta)}{x^2},$$

$$P[\bar{\nu}_\mu \rightarrow \bar{\nu}_e] = P[\nu_\mu \rightarrow \nu_e] \text{ with } \delta \rightarrow -\delta \text{ and } x \rightarrow -x.$$
For $L = 1200$ km ($\sim$ Fermilab to DUSEL),
and $\sin^2 2\theta_{13} = 0.04$

(Parke)

Note how the 2nd maximum can help.
What Facility Is Needed?

$$P(\nu_\mu \rightarrow \nu_e) \sim \sin^2 2\theta_{13}$$

A conventional accelerator neutrino beam from $\pi$ and $K$ decay is mostly $\nu_\mu$, but has a $\sim 1\%$ $\nu_e$ contamination.

Studying $\nu_\mu \rightarrow \nu_e$ with a conventional beam would be difficult if $\sin^2 2\theta_{13} < 0.01$.

More Powerful Facilities

$\beta$ Beam: $\beta^+$ emitting nuclei in a storage ring produce a flavor-pure $\nu_e$ beam. Look for $\nu_e \rightarrow \nu_\mu$.

The decays $\mu^+ \rightarrow e^+ \nu_e \bar{\nu}_\mu$ of muons in a storage ring, plus a magnetized detector with $\mu^+/\mu^-$ discrimination, yields an effectively flavor-pure $\nu_e$ beam. Look for $\nu_e \rightarrow \nu_\mu$.39
<table>
<thead>
<tr>
<th>( \sin^2 2\theta_{13} )</th>
<th>\text{Use}</th>
</tr>
</thead>
<tbody>
<tr>
<td>( &gt; 10^{- (2-3)} )</td>
<td>(Conventional) Superbeam</td>
</tr>
<tr>
<td>( &lt; 10^{- (2-3)} )</td>
<td>( \beta ) Beam or ( \nu ) Factory</td>
</tr>
</tbody>
</table>
# Timelines For Near-Term Experiments

**Reactor probes of $\theta_{13}$**

<table>
<thead>
<tr>
<th>Experiment</th>
<th>Start</th>
<th>Ultimate 90% CL Sensitivity</th>
<th>Year</th>
</tr>
</thead>
<tbody>
<tr>
<td>Double CHOOZ</td>
<td>2011</td>
<td>0.03</td>
<td>2016</td>
</tr>
<tr>
<td>RENO</td>
<td>2010</td>
<td>0.02</td>
<td>??</td>
</tr>
<tr>
<td>Daya Bay</td>
<td>2012</td>
<td>0.01</td>
<td>2016</td>
</tr>
</tbody>
</table>
Accelerator experiments

T2K: A probe of $\theta_{13}$. Already started, at low beam power. Ultimate 90% CL sensitivity to $\sin^2 2\theta_{13} \sim 0.01$, depending on $\delta_{CP}$. Year: 2016 (my guess).

NOνA: A probe of $\theta_{13}$ and of the mass ordering. Start in 2012. $\theta_{13}$ sensitivity comparable to T2K. Mass ordering determination requires $\theta_{13}$ close to the present bound. Year: 2019 (my guess).
Summary of sensitivities to $\theta_{13}$ vs. time
Long-Term Future Plans
Asia: 3 sites under consideration

Water Cherenkov

Liquid Ar TPC

Korea

Okinoshima

Kamioka

1000km
1deg. Off-axis

658km
0.8deg.
almost On-axis

295km
2.5deg. Off-axis

KEK
J-PARC

(Y.-K. Kim)

NP08 is 'The 4th International Conference on Nuclear and Particle Physics'
U.S. Plans

The Long Baseline Neutrino Experiment (LBNE)

(INT Workshop August 9–11)

0.7 MW wide-band beam, upgradable to 2 MW (Project X)

100 kTon water C, or 17 kTon LAr, detectors in DUSEL, 1300 km from Fermilab

Start ~ 2020. Run for 6+ years.

Possible synergy with DAEdALUS

(INT Workshop August 5–6)
Long Baseline Neutrino Experiment

(Strait)
DAEdALUS —

*Short*-Baseline Measurements, But Still Near L/E of First Maximum

Medical, homeland security cyclotrons

<table>
<thead>
<tr>
<th>3 cyclostrons</th>
<th>2 cyclostrons</th>
<th>1 cyclotron</th>
</tr>
</thead>
<tbody>
<tr>
<td>20km</td>
<td>8km</td>
<td>1.5km</td>
</tr>
</tbody>
</table>

Compare $e^+$ production on and off Max.
The 3σ Reach of Successive Phases

TheReach of Successive Phases

\[ \sin^2 2\theta_{13} \]

Mass Ordering

\[ \text{Discovery Potential sign} \sqrt{m_1^2} \]

CP Violation

\[ \text{3σ Discovery Potential for } \delta \neq 0 \text{ and } (\varepsilon \pi) \]

N. Saoulidou
The European Strategy

Long term strategy planning

• It is unrealistic to expect to have a high intensity neutrino source of any kind in Europe before early 2020’s.

• By this time it is reasonable to expect that there will be many years of operating and upgrading Superbeams in Japan and in the USA. This should be closely followed.

• Thus if Europe is to be competitive in the 2020’s it should concentrate on the R&D for a new intense source, i.e. the Neutrino Factory or the Beta Beam. It would be advisable to systematically review the progress and prospects of this work.

(From Report of the SPC ν Panel)
We Must Be Alert To Surprises!
MINOS may get $P(\bar{\nu}_\mu \rightarrow \bar{\nu}_\mu) \neq P(\nu_\mu \rightarrow \nu_\mu)$.
MiniBooNE $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ search shows excess compatible with LSND

(Van de Water at Neutrino 2010)
Conclusion

We should have an interesting few weeks at the INT!