Tensions With the 3 – ν Paradigm

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EW Moriond 2012
Thanks to the Moriond organizers for quite a few things …

Thanks to Alan Bross, Patrick Huber, Georgia Karagiorgi, and Joachim Kopp for inputs.
The Three - Neutrino Paradigm
The \((\text{Mass})^2\) Spectrum

\[\nu_3 \quad \text{or} \quad \nu_1 \nu_2 \nu_3\]

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

Normal

\[\Delta m_{21}^2 \approx 7.4 \times 10^{-5} \text{ eV}^2, \quad \Delta m_{32}^2 \approx 2.3 \times 10^{-3} \text{ eV}^2\]

Inverted
The Interactions

The interactions of the neutrinos are assumed to be those of the Standard Model (SM), modified to incorporate leptonic mixing.
The neutrino couplings to the W:

\[ l_e \equiv e, \ l_\mu \equiv \mu, \ l_\tau \equiv \tau \]

But the neutrinos \( \nu_{\alpha} \) of definite flavor
are superpositions of the neutrinos of definite mass:

\[ |\nu_\alpha> = \sum_i U^{*\alpha i} |\nu_i> \]

Neutrino of flavor \( \alpha = e, \mu, \text{ or } \tau \)
Unitary leptonic mixing matrix

Neutrino of definite mass
The neutrino couplings to the Z:

\[ Z \rightarrow A\delta_{ij} \nu_j \]  

\[ Z \rightarrow A\delta_{\alpha\beta} \nu_\beta \]  

\[ Z \rightarrow A\delta_{i\tau} \nu_\tau \]

**Oscillation among** \( \nu_e, \nu_\mu, \) and \( \nu_\tau \)** does not change the Neutral Current event rate.**
The Mixing Matrix $U$

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

$c_{ij} \equiv \cos \theta_{ij}$
$s_{ij} \equiv \sin \theta_{ij}$

$$\begin{bmatrix} e^{i\alpha_1/2} & 0 & 0 \\ 0 & e^{i\alpha_2/2} & 0 \\ 0 & 0 & 1 \end{bmatrix}$$

Doesn’t affect oscillation

$$\theta_{12} \approx 34^\circ, \quad \theta_{23} \approx 39-51^\circ,$$

$$\sin^2 2\theta_{13} = 0.092 \pm 0.023 \text{ (stat)} \pm 0.005 \text{ (syst)} \quad \text{(Daya Bay)}$$

$\delta$ and $\theta_{13} \neq 0$ would lead to $P(\overline{\nu}_\alpha \rightarrow \overline{\nu}_\beta) \neq P(\nu_\alpha \rightarrow \nu_\beta)$. $CP$ violation
The Implications of the Value of $\theta_{13}$

With $\sin^2 2\theta_{13}$ not much below 0.1, NOvA has a good shot at determining whether the neutrino mass spectrum looks like $\underline{\phantom{0}}$ or $\underline{\phantom{0}}$.  

(Mark Messier’s talk)

The evidence now seems quite strong that $\sin^2 2\theta_{13} > 0.01$.

This is very encouraging for experiments that propose to look for CP violation in neutrino oscillation by comparing $\overline{\nu}_\mu \rightarrow \overline{\nu}_e$ with $\nu_\mu \rightarrow \nu_e$. 
$$P(\nu_\mu \rightarrow \nu_e) \sim \sin^2 2\theta_{13}$$

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 have been difficult if $\sin^2 2\theta_{13}$ had been less than 0.01.
Why CP Violation (CP) In Neutrino Oscillation Would Be Very Interesting

It would establish that CP is not special to quarks.

A major motivation to look for it:

- Its observation would make it more plausible that —
  - the baryon-antibaryon asymmetry of the universe —
  - arose, at least in part, through Leptogenesis.
Leptogenesis

Explains the baryon-antibaryon asymmetry of the universe by CP-violating heavy neutrino decays.

The SM Sphaleron process converts part of this asymmetry into the observed baryon-antibaryon asymmetry.

Generically, leptogenesis and light-neutrino CP imply each other.
The 3-ν paradigm successfully describes many experimental results, but not all.
The Non-SM

\[ P(\bar{\nu}_\mu \rightarrow \bar{\nu}_\mu) \neq P(\nu_\mu \rightarrow \nu_\mu) \]

Possibility
Oscillation

When the neutrino spectrum has effectively only 2 levels

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

\[ P(\nu_\alpha \rightarrow \nu_\alpha) = 1 - \sin^2 2\theta_{\alpha\alpha} \sin^2 \left[ 1.27 \Delta m^2 \left( eV^2 \right) \frac{L(km)}{E(GeV)} \right] \]
MINOS: **Maybe** $P(\bar{\nu}_\mu \to \bar{\nu}_\mu) \neq P(\nu_\mu \to \nu_\mu)$

Non-SM neutrino interactions?? (Kopp, Machado, Parke)
MINOS may find $P(\bar{\nu}_\mu \rightarrow \bar{\nu}_\mu) \neq P(\nu_\mu \rightarrow \nu_\mu)$

$\nu_\tau + N \rightarrow X + \mu$  
(Kopp, Machado, Parke)
MINOS: With 70% More $\bar{\nu}$ Data
Are There More Than 3 Mass Eigenstates?

Are There Sterile Neutrinos?
**Sterile Neutrino**

One that does not couple to the SM $W$ or $Z$ boson

A “sterile” neutrino may well couple to some non-SM particles. These particles could perhaps be found at LHC or elsewhere.
The Hint From LSND

The LSND experiment at Los Alamos reported a rapid $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ oscillation at $L(km)/E(GeV) \sim 1$.

$$P(\bar{\nu}_\mu \rightarrow \bar{\nu}_e) = \sin^2 2\theta \sin^2 \left[1.27\Delta m^2(eV^2) \frac{L(km)}{E(GeV)}\right] \sim 0.26\%$$

From $\mu^+$ decay at rest; $E \sim 30$ MeV

$\sim 1eV^2$ in contrast to $\Delta m^2_{32} = 2.3 \times 10^{-3} eV^2$, $\Delta m^2_{21} = 7.4 \times 10^{-5} eV^2$

At least 4 mass eigenstates

{from measured $\Gamma(Z \rightarrow \nu\bar{\nu})$} At least 1 sterile neutrino
The LSND-favored region

Not relevant if CP is violated
The Hint From MiniBooNE

In MiniBooNE, both $L$ and $E$ are $\sim 17$ times larger than they were in LSND, and $L/E$ is comparable.

MiniBooNE has reported both $\nu_\mu \rightarrow \nu_e$ and $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ results.
MiniBooNE $\nu_\mu \rightarrow \nu_e$ Search

No excess above background above 0.475 GeV.
MiniBooNE $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ Search; 2010 Results


The $\nu$ and $\bar{\nu}$ results can differ due to CP violation.
MiniBooNE $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ Search; 2011 Results

Any excess is small.

E. Zimmerman and M. Shaevitz at PANIC 2011
The Hint From Reactors

The prediction for the un-oscillated $\bar{\nu}_e$ flux from reactors, which has $\langle E \rangle \sim 3$ MeV, has increased by about 3%.

(Mueller et al., Huber)

Measurements of the $\bar{\nu}_e$ flux at $(10 - 100)$m from reactor cores now show a $\sim 6\%$ disappearance.

(Mention et al.)
Disappearance at $L(\text{m})/E(\text{MeV}) \geq 1$ suggests oscillation with $\Delta m^2 \geq 1 \text{ eV}^2$, like LSND and MiniBooNE.

Oscillation with only $3\nu$ and $\sin^2 2\theta_{13} = 0.06$

Oscillation with $4\nu$ and one $\Delta m^2 >> 1 \text{ eV}^2$
The Hint From $^{51}$Cr and $^{37}$Ar Sources

These radioactive sources were used to test gallium solar $\nu_e$ detectors.

\[
\frac{\text{Measured event rate}}{\text{Expected event rate}} = 0.86 \pm 0.05
\]

(Giunti, Laveder)

Rapid disappearance of $\nu_e$ flux due to oscillation with a large $\Delta m^2$??
The Hint From Cosmology

Big Bang Nucleosynthesis (BBN) and CMB anisotropies count the effective number of relativistic degrees of freedom, $N_{\text{eff}}$, at early times.

Light sterile neutrinos mixed with the active ones as required by the terrestrial anomalies would very likely have thermalized in the early universe.

Then $N_{\text{eff}}$ grows by 1 for each sterile species.

The evidence suggests that perhaps $N_{\text{eff}} > 3$. 
### $N_{\text{eff}}$ From BBN

<table>
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<tr>
<th>Model</th>
<th>Data</th>
<th>$N_{\text{eff}}$</th>
<th>Ref.</th>
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<tbody>
<tr>
<td>$\eta + N_{\text{eff}}$</td>
<td>$\eta_{\text{CMB}} + Y_p + D/H$</td>
<td>$3.8^{(+0.8)}_{(-0.7)}$</td>
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<td>$\eta_{\text{CMB}} + Y_p + D/H &lt; (4.05)$</td>
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<tr>
<td></td>
<td>$Y_p + D/H$</td>
<td>$3.82 \pm 0.35$</td>
<td>[13]</td>
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<td></td>
<td></td>
<td>$3.13 \pm 0.21$</td>
<td>[13]</td>
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<td>$\eta + N_{\text{eff}}, (\Delta N_{\text{eff}} \equiv N_{\text{eff}} - 3.046 \geq 0)$</td>
<td>$\eta_{\text{CMB}} + D/H$</td>
<td>$3.8 \pm 0.6$</td>
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<td>$\eta_{\text{CMB}} + Y_p$</td>
<td>$3.90^{+0.21}_{-0.58}$</td>
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<td>$Y_p + D/H$</td>
<td>$3.91^{+0.22}_{-0.55}$</td>
<td>[12]</td>
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$N_{\text{eff}}$ From CMB

<table>
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<tr>
<td>$N_{\text{eff}}$</td>
<td>W-5+BAO+SN+$H_0$</td>
<td>$4.13^{+0.87}_{-0.85}^{(+1.76)}$</td>
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<td>W-5+CMB+BAO+XLF+$f_{\text{gas}}$+$H_0$</td>
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<td>W-7+ACT</td>
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<td>$N_{\text{eff}}+f_{\nu}$</td>
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<td>$N_{\text{eff}}+\Omega_k$</td>
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<tr>
<td>$N_{\text{eff}}+f_{\nu}+\omega$</td>
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<td>$3.68^{(+1.90)}_{(-1.84)}$</td>
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<td>W-7+CMB+LRG+$H_0$</td>
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<td>$N_{\text{eff}}+\Omega_k+f_{\nu}+\omega$</td>
<td>W-7+CMB+BAO+SN+$H_0$</td>
<td>$4.2^{(+1.10)}_{(-0.61)}^{(+2.00)}$ $^{(-1.14)}$</td>
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<td>W-7+CMB+LRG+SN+$H_0$</td>
<td>$4.3^{(+1.40)}_{(-0.54)}^{(+2.30)}$ $^{(-1.09)}$</td>
<td>[33]</td>
</tr>
</tbody>
</table>

More precise information will come from the Planck satellite.
\[ \sum_{i} m(\nu_i) \] In the Early Universe

Large Scale Structure in the universe and the CMB suggest that —

\[ \sum_{i} m(\nu_i) < (0.17 - 1.0) \text{ eV} \]

(Seljak, Slosar, McDonald)
(Hannestad; Pastor)

Possible tension with terrestrial experiments if \( \Delta m^2 > 1 \text{ eV}^2 \).

However, in cosmology, there are parameter degeneracies.
Global Fits To Short-Baseline Terrestrial Data
The Spectra That Are Tried

\[ \nu_1, \nu_2, \nu_3, \nu_4, \nu_5 \]

\[ 3 + 1 \] \hspace{1cm} \text{No CP}

\[ 3 + 2 \] \hspace{1cm} \text{CP Possible}

Short-Baseline experiments have an L/E too small to see the splitting between \( \nu_1, \nu_2, \) and \( \nu_3. \)
The Bottom Line

3 + 1 spectra do not provide a good fit to all the data.

They do not violate CP.

They cannot accommodate the CP-violating simultaneous presence of a $\bar{\nu}$ signal in LSND and MiniBooNE, and the absence of a $\nu$ signal in MiniBooNE.

(Karagiorgi; Kopp, Maltoni, and Schwetz)
$3 + 2$ spectra can violate CP, so they do better, but there is still tension between appearance data and disappearance data.

Other phenomenological models are being tried ....
So, Are There Sterile Neutrinos?
Not speaking for anybody else, my personal impression is —

Individually or taken together, the hints are certainly not convincing.

But —

They are interesting enough to call for further, hopefully definitive, investigation.
From the charge:

“… consider new generation detectors and/or new types of neutrino sources that would lead to a definitive resolution of the existing anomalies.”

Started ~ January, 2012

Report due ~ May, 2012
Ideas For Future Experiments
I would just like to illustrate the **diversity** of ideas being proposed.
This process has the same rate for any incoming *active* neutrino, $\nu_e$, $\nu_\mu$, or $\nu_\tau$.

But the Z does not couple to $\nu_{sterile}$.

If $\nu_{active} \rightarrow \nu_{sterile}$, the coherent scattering event rate will oscillate with it.
Ideas—

**Electron-capture monoenergetic $\nu_e$ source**
Kinetic energy of nuclear recoil $\sim$ Few x 10 eV.
Use bolometric cryogenic detector.

(Formaggio et al.)

**Cyclotron pion & muon decay-at-rest neutrino source**
Two sources — one detector
Kinetic energy of nuclear recoil $\sim$ keV.
Detection via DM-inspired detectors.

(Anderson et al.)

*Caveat: If $\Delta m^2 >> 1$ eV$^2$, the oscillation may be too fast to see.*
For $E \sim 30$ MeV $\bar{\nu}_\mu$ from $\mu^+$ decay at rest, and $\Delta m^2 \sim 1$ eV$^2$, the oscillation maximum is at $\sim 40$ m.

(Agarwalla et al.)
Two-Detector Short Baseline Experiments At Accelerators

Compare event rates in a near and a far detector.

This is a good way to deal with flux uncertainties, so long as the neutrinos have not already oscillated before reaching the near detector.

Idea —
Two ICARUS detectors in the CERN PS beam

\[ \overline{\nu}_e \]

- 90% CL limit, \( E_\nu^{QE} > 200 \text{ MeV} \)
- 90% CL limit, \( E_\nu^{QE} > 475 \text{ MeV} \)
- KARMEN 90% CL
- BUGEY 90% CL

DOUBLE-LAr
@ CERN-PS

- LSND 90% C.L.
- LSND 99% C.L.

5 \times 10^{20} \text{ POT}

(ICARUS)
Two LAr detectors in the FNAL Booster beam

(Guenette et al.)
A Very Low Energy Neutrino Factory

$E_\mu = (2 - 3) \text{ GeV}$

If store $\mu^+$, can study—

$\mu^+ \rightarrow e^+ + \nu_e + \bar{\nu}_\mu$

followed by —

$\nu_e \rightarrow \nu_\mu$.  

LSND reported $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$.  

$P(\nu_e \rightarrow \nu_\mu) = P(\bar{\nu}_\mu \rightarrow \bar{\nu}_e)$
(Bross et al.)
Summary

There are interesting tensions with the $3 - \nu$ paradigm.

Hopefully we will be able to determine what is behind them in the not too distant future.