Why accelerator-based oscillation physics may be the best place to find

The Next Real Surprise!

Janet Conrad,
Columbia University
Because...
Neutrinos are a relatively unexplored frontier and
Accelerators are developing so rapidly

There is a special opportunity here
to find something really unexpected
Recent technology revolutions for accelerator-based neutrinos:

- Nearly MegaWatt beams
  (with the promise of Multi-MegaWatts soon: SC RF Linacs, etc.)
- Improved secondary focusing
- Selectable energy ranges, narrow band beams
- GPS
- High statistics 2ndary production and xsec experiments
  (e.g. HARP, BNL-E910, MIPP, FINeSSE...)
- Innovative ideas for even better accelerators:
  FFAG, neutrino factory, beta beams
Opening Up Opportunities
Using Accelerator-based
Oscillations Searches....

Soon:   MiniBooNE
Near Term: Minos, Opera, T2K, Nova
Long Term: Neutrino Factory, Beta Beam

The opportunity for surprise extends beyond oscillation searches too...
See talk by Mike Shaevitz
It would be a big surprise if ....

I'll eat my hat

LSND was RIGHT
Nearly 49,000 Coulombs of protons on upstream target

Neutrino Energy
20-55 MeV,

Baseline 30 m

167 tons Liquid scintillator

1220 phototubes

$\bar{\nu}_e$ events observed in a $\bar{\nu}_\mu$ beam ???

$87.9 \pm 22.4 \pm 6.0$ (4.$\sigma$)

$P(\nu_\mu \rightarrow \nu_e) = \sin^2 2\theta \sin^2(1.27\Delta m^2 L/E)$
Problem:

\[ \Delta m_{13}^2 = \Delta m_{12}^2 + \Delta m_{23}^2 \]

If LSND is not due to a fluctuation or an unknown systematic

★ It must be new physics.
★ It could be new muon-decay physics (TWIST)
★ It could be new oscillation physics (MiniBooNE)

(or one of the other results must change due to systematics or new physics)
MiniBooNE:

\[ P(\nu_\mu \rightarrow \nu_e) = \sin^2 2\theta \sin^2 (1.27 \Delta m^2 L/E) \]

Keep L/E same while changing systematics
The MiniBooNE Beam:

- Produced via 8 GeV protons on tgt
- Secondary production measured at the HARP experiment:
- Focusing via a horn
- 50 m decay path for secondaries
- in-situ kaon decay monitor

\[ E \sim 1\text{GeV} \]
The MiniBooNE Detector

- 12 meter diameter sphere
- Filled with 950,000 liters of undoped mineral oil
  (events produce both Cerenkov and Scintillation $\gamma$'s)
- Light tight inner tank with 1280 photomultiplier tubes
- Outer veto region with 240 PMTs.
- We measure charge and time for each tube

Many in situ monitoring systems...
Right now: Calibration & Cross Section Studies:

\[ \nu + (p/n) \rightarrow \nu + \Delta \]
\[ \Delta \rightarrow (p/n) + \pi^0 \]

coherent:
\[ \nu + C \rightarrow \nu + C + \pi^0 \]

resonant:

Crucial if we plan to do *precision* oscillation physics!
Updated Appearance Sensitivity

- $\nu_e$ signal and background breakdown
- $\nu_e$ signal events
- NC $\pi^0$ misIDs
- Beam $\nu_e$ events

- Reasonable signal separation with $10^{21}$ POT
There are sterile neutrinos

It would be a big surprise if ....

Not a chance!
Z decay indicates 3 active neutrinos!

Another neutrino with m<45 GeV will have to be sterile

But it could mix with the others...

\[
\begin{pmatrix}
\nu_e \\
\nu_\mu \\
\nu_\tau \\
\nu_s
\end{pmatrix}
= 
\begin{pmatrix}
U_{e1} & U_{e2} & U_{e3} & U_{e4} \\
U_{\mu1} & U_{\mu2} & U_{\mu3} & U_{\mu4} \\
U_{\tau1} & U_{\tau2} & U_{\tau3} & U_{\tau4} \\
U_{s1} & U_{s2} & U_{s3} & U_{s4}
\end{pmatrix}
\begin{pmatrix}
\nu_1 \\
\nu_2 \\
\nu_3 \\
\nu_4
\end{pmatrix}
\]

...thus be observed via oscillations
Why search?

Interesting from a theoretical point of view:
- The simplest extension to a model with neutrino mass
- Sterile neutrinos "fall out" of GUTS and Extra Dimensions Theories

- Why should the sterile neutrino be light? maybe a new symmetry
- Why not massless? maybe Planck scale corrections

- They can improve models for the R-process in supernovae (which requires oscillations)

From Strumia, Neutrino '04:

Ye = 1/(1+(n/p))
(Ye small has neutron excess)

for the number $n_s$ of $\nu_s$ with masses $m_s$ and mixings $\theta_s$ are not very restrictive

$0 \leq n_s < \infty \quad 0 \leq m_s < \infty \quad 0 \leq \theta_s < 360^\circ$
Luckily, Experiments are more restrictive/suggestive!

Short baseline experiments:

<table>
<thead>
<tr>
<th>Channel</th>
<th>Experiment</th>
<th>Lowest $\Delta m^2$ Reach (90% CL)</th>
<th>$\sin^2 2\theta$ Constraint (90% CL)</th>
<th>Optimal $\Delta m^2$</th>
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<tr>
<td>$\nu_\mu \rightarrow \nu_e$</td>
<td>LSND</td>
<td>$3 \cdot 10^{-2}$</td>
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<td>$&gt; 1.2 \cdot 10^{-3}$</td>
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<td></td>
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<td>$&lt; 1.0 \cdot 10^{-3}$</td>
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<tr>
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<td>$&lt; 1.4 \cdot 10^{-1}$</td>
<td>$&lt; 1.3 \cdot 10^{-2}$</td>
</tr>
<tr>
<td></td>
<td>CHOOZ</td>
<td>$7 \cdot 10^{-4}$</td>
<td>$&lt; 1.0 \cdot 10^{-1}$</td>
<td>$&lt; 5 \cdot 10^{-2}$</td>
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<tr>
<td>$\nu_\mu \rightarrow \nu_\mu$</td>
<td>CCFR84</td>
<td>$6 \cdot 10^0$</td>
<td>none</td>
<td>$&lt; 2 \cdot 10^{-1}$</td>
</tr>
<tr>
<td></td>
<td>CDHS</td>
<td>$3 \cdot 10^{-1}$</td>
<td>none</td>
<td>$&lt; 5.3 \cdot 10^{-1}$</td>
</tr>
<tr>
<td>$\nu_\mu \rightarrow \nu_\tau$</td>
<td>NOMAD</td>
<td>$7 \cdot 10^{-1}$</td>
<td>$&lt; 3.3 \cdot 10^{-4}$</td>
<td>$&lt; 2.5 \cdot 10^{-4}$</td>
</tr>
<tr>
<td></td>
<td>CHORUS</td>
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<td>$&lt; 6.8 \cdot 10^{-4}$</td>
<td>$&lt; 4.5 \cdot 10^{-4}$</td>
</tr>
<tr>
<td>$\nu_e \rightarrow \nu_\tau$</td>
<td>NOMAD</td>
<td>$6 \cdot 10^0$</td>
<td>$&lt; 1.5 \cdot 10^{-2}$</td>
<td>$&lt; 1.1 \cdot 10^{-2}$</td>
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<td>$&lt; 4 \cdot 10^{-2}$</td>
</tr>
</tbody>
</table>

Limits ~90% CL from atmospheric < 30% solar < 10%

This pulls the fit at about 20 eV$^2$

Treat LSND as a positive signal

CDHS sees an effect in LSND mass range (near detection $2\sigma$)

(Sorel, Conrad, Shaevitz., hep-ph/0305255)
3+1 Models do not show high compatibility...

3+2 Models do show compatibility....

Best Fit: $\Delta m_{41}^2 = 0.92 \text{ eV}^2$, $U_{e4} = 0.121$, $U_{\mu 4} = 0.204$, $\Delta m_{51}^2 = 22 \text{ eV}^2$, $U_{e5} = 0.036$, $U_{\mu 4} = 0.224$
What does this mean for cosmology?

The latest from BBN fits:
Cyburt, Fields, Olive, Skillman, astro-ph/0408033
at 68% CL (1σ) \(2.67 < N_v < 3.85\)

There are mechanisms which substantially reduce cosmic \(\nu\)'s

- K. Abazajian hep-ph/0307266
- J. Beacom, astro-ph/0404585
- R. Mohapatra, hep-ph/047194

Including CMB/LSS too:

Need to vary \(H_0\) in global fits as you vary the mass,\

\[\text{Hannestad astro-ph/0303076}\]

...It would mean we'd have a lot of surprised cosmologists!
It would be a big surprise if ....

That can't be true!
\[ \nu_2 \rightarrow \nu_3 + \text{J} \]

Implies a non-zero mass difference between 2 neutrino states:

\[ \delta m_{23}^2 = m_2^2 - m_3^2, \]

Which means mixing is possible as well:

\[ \nu_\mu = \cos \theta \nu_2 + \sin \theta \nu_3. \]

So the most general formula for survival probability would be:

\[ P(\nu_\mu \rightarrow \nu_\mu) = \sin^4 \theta + \cos^4 \theta e^{-\alpha L/E} + 2 \sin^2 \theta \cos^2 \theta e^{-\alpha L/2E} \cos \left( \frac{\delta m_{23}^2 L}{2E} \right) \]

Where the lifetime appears as:

\[ \alpha = m_2/\tau_2 \]

And is assumed to be a function of the 2 neutrino masses
Isn't neutrino decay already ruled out by Super K?

Best fit oscillation:

\[ \chi^2/\text{dof} = 37.9/40 \quad (\text{Prob} = 56\%) \]

Errors are statistical only

Neutrino Decay:

\[ \chi^2/\text{dof} = 49.1/40 \quad (\text{Prob} = 15\%) \]

Errors are statistical only

There is 3\(\sigma\) between \(\chi^2_{\text{min}}\) but...

Fit, including systematic errors...

hep-ph/0404034
The ideal place to look:

Long Base Line experiments:

An idea pioneered by K2K...

who showed a $3.9\sigma$ osc. signal at Nu'04!

Expected: $150 \pm 11.6$

- $N_{SK}^{obs} = 108$
- $N_{SK}^{exp \ (best \ fit)} = 104.8$

But not enough statistics to differentiate decay from oscillations...
The Next to Turn On: NuMI/Minos

Far Detector: segmented Iron calorimeter detector

Near Detector

Fermilab \( \rightarrow \) Soudan

10 km

730 km

12 km

Beam begins Jan '05

running with cosmic \( \nu \)s now....

upward going neutrino rates compared to Bartol'96 flux

8m octagonal steel & scintillator tracking calorimeter

Magnetized Iron (B~1.5T)

484 planes of scintillator

PRELIMINARY
Neutrino decay in NuMI/Minos

Solid histogram: Flux at Soudan with no osc or other new physics,
Dashed: Flux with oscillations (SK best fit)  • • • • • • •
Points: Flux for neutrino decay  ●

There is a big difference between the models at low energy!
It would be a big surprise if ..., \( \theta_{23} \) is exactly 45°.

No Way!
None of the "well–measured" angles in the quark sector or the neutrino sector, are "maximal"

...Except, for, possibly, the atmospheric oscillation

WHY MAXIMAL MIXING?
see Grimus, hep-ph/0405261
A new symmetry group, eg: $Z_2, D_4$ models
Is it maximal mixing?

Expected **MINOS** capability:
- solid = 90% CL
- $d(\sin^2 2\theta_{23}) \sim 5\%$
- with $25\times10^{20}$ protons on target (~6 years)

**SK**: 90% CL and best fit (⭐)

**NuMI** running will be $4\times10^{20}$ p.o.t/year

**OPERA** data can be combined also $\nu_\mu \rightarrow \nu_\tau$ appearance

Begins in 2006
And T2K can improve on this further!

Plan is to use a 2.5° off-axis beam & the existing Super K detector

Approved Dec, 2003
Expected to run: 2009
\( \nu_\mu \) disappearance

\[ \delta(\sin^2 2\theta_{23}) \]

OA 2.5deg.

\[ \delta(\sin^2 2\theta_{23}) \sim 0.01 \]
\[ \delta(\Delta m^2) < 1 \times 10^{-4} \text{(eV}^2\text{)} \]

\[ \text{True } \Delta m^2_{23} (10^{-3} \text{eV}^2) \]

\[ 1 \times 10^{-4} \]

\[ \Delta m^2 (\text{eV}^2) \]

Soudan

Macro

\( \sin^2 (2\theta) \)
CP violation is HUGE in the lepton sector. It would be a big surprise if ....

You're kidding me!
The Mixing Matrix:

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

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

\[ s_{13} \text{ has to be large (>1%) to have a chance at all!} \]
CP violation

\[ P_{\text{osc}}(\nu_\alpha \rightarrow \nu_\beta) \neq P_{\text{osc}}(\bar{\nu}_\alpha \rightarrow \bar{\nu}_\beta) \]

\[ \Delta m^2 < 0 \quad \Delta m^2 > 0 \]

To untangle, you need different baselines!

- T2K
- Nova (Proposed off-axis FNAL-Minn.)
Can we tell at $3\sigma$ that $\delta \neq 0$ or $\pi$??

With a Multi-MegaW Proton Driver

For nature's real values of $\delta$ and $\sin^2 2\theta_{13}$, the experiment can see that $P_\nu \neq P_{\bar{\nu}}$ at $3\sigma$

Nature's real value

large medium & small reactor expt. sensitivity
If the CP Violation signal is not 90 or 270 degrees, How can we see it?

VLBνO

2450km baseline
1MW source
½MT detector
5×10^7 sec exposure
We saw something even stranger!

It would be a big surprise if....

Try to be practical!
To go further we will need The Next Generation of accelerators....

A Neutrino Factory or A Beta Beam Facility

⭐ High Intensity
⭐ Well defined flavor content
⭐ Well defined energy distribution
You're kidding me!

No Way!

Not in my lifetime!

I'll eat my hat

Gimme a break!

Not a chance!
<table>
<thead>
<tr>
<th></th>
<th>LSND</th>
<th>sterile</th>
<th>decay</th>
<th>max. mix</th>
<th>CPV</th>
<th>Beyond!</th>
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<td>MiniBooNE</td>
<td>✈️</td>
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</tbody>
</table>

Accelerator-based oscillation studies may be the **best**, **most versatile** way to search for the **next BIG surprise**!
Backup Slides
Theoretical Justification for 3+2 .... examples from the last 6 months

THE STERILE NEUTRINO: FIRST HINT OF 4TH GENERATION FERMIONS?

LARGE MIXING FROM SMALL: PSEUDODIRAC NEUTRINOS AND THE SINGULAR SEESAW.
By G.J. Stephenson, Jr. (New Mexico U.), T. Goldman (Los Alamos), B.H.J. McKellar, M. Garbutt (Melbourne U.),

TWO LIGHT STERILE NEUTRINOS THAT MIX MAXIMALLY WITH EACH OTHER AND MODERATELY
WITH THREE ACTIVE NEUTRINOS.
e-Print Archive: hep-ph/0402183

(3+2) NEUTRINO SCHEME FROM A SINGULAR DOUBLE SEESAW MECHANISM.
e-Print Archive: hep-ph/0401241

SIMPLE MODEL FOR (3+2) NEUTRINO OSCILLATIONS.
e-Print Archive: hep-ph/0312285
CPT Violation

**Mass Spectrum Model:**
hep-ph/0210411  Barenboim, Lykken
disfavored unless steriles are also invoked
hep-ph/0308299, Barger, Marfatia, Whisnant

**Lorentz Invariance Violation:**
Kostelecky and Mewes, hep-ph/0308300
Fits to neutrino data can, in principle, accommodate an LSND signal

**Quantum Gravity Decoherence Model:**
Additional mixing induced by singular space-time configurations (wormholes, microscopic black holes, geons = "space time foam")
fit to data: $\chi^2/DOF = 60.7/56$  hep-ph/0404014, 0406035 Barenboim, Mavromatos
TWIST:

Experimental Evidence for the Absence of a weak exchange particle with right-handed couplings

D0 Experiment (Fermilab)
Limit of Sensitivity
(dependence on assumptions for the right-handed CKM matrix)

Strovink Experiment (TRIUMF)
Limit of Sensitivity
(green region was searched)
(yellow region was searched)

E614 - Precision $\pi^+$ Decay at TRIUMF
Discovery Potential
Sensitive to Red Region
-- which has not yet been studied

Limits of E614 Sensitivity
- some model dependence
CP Violation in $3+2$

& MiniBooNE antineutrino running:

$$P_{\text{osc}}(\nu_\alpha \to \nu_\beta) \neq P_{\text{osc}}(\bar{\nu}_\alpha \to \bar{\nu}_\beta)$$

Sorel and Whisnant, preliminary
How the Nova sensitivity was calculated:

Code: a package written by Mike Shaevitz for APS Nu Study.
(includes osc. prob. code from S.Parke)

Purpose: Study relative contributions of Reactor, T2K, Nova to atmospheric $\Delta m^2$ studies individually, in groups, as fn of time.

Agreement between Groups:
A meeting between representatives of the SuperBeams and Reactor APS Study Groups (SW, JC, DM, BM/MD, GB, EB, MS, GF) led to agreement on this code, statistical methods & presentation layout.

How the code works, in general:

1) Generate data (osc. probs) for a given point in $\delta$ and $\sin^2\theta_{13}$ space.
2) Find the minimum $\chi^2$ demanding $\delta=0$ but allowing $\theta_{13}$ and $\theta_{23}$ to vary.
3) The $2\sigma$ limit curve is where the $\chi^2=4$.
The main focus of MiniBooNE right now: Precision modeling/understanding of beam and detector...

Secondary Production Model: new data from BNL 910

Calibration:
- Michel electrons
- Tracker & Cube system

Optical Model:
- Light Creation
  - Cerenkov
  - Scintillation
- Light Propagation
  - Fluorescence
  - Scattering
  - Absorption

![Graph](image1.png)

![Graph](image2.png)