MiniBooNE and Sterile Neutrinos

M. Shaevitz
Columbia University
Oxford Seminar June 23, 2004

- Extensions to the Neutrino Standard Model: Sterile Neutrinos
- MiniBooNE: Status and Prospects
- Future Directions if MiniBooNE Sees Oscillations
Theoretical Prejudices before 1995

• Natural scale for $\Delta m^2 \sim 10 - 100 \text{ eV}^2$
  since needed to explain dark matter

• Oscillation mixing angles must be small
  like the quark mixing angles

• Solar neutrino oscillations must be
  small mixing angle MSW solution
  because it is “cool”

• Atmospheric neutrino anomaly must be
  other physics or experimental problem
  because it needs such a large mixing angle

• LSND result doesn’t fit in so must not
  be an oscillation signal
### Theoretical Prejudices before 1995

| Natural scale for $\Delta m^2 \sim 10 - 100$ eV$^2$ since needed to explain dark matter | Wrong |
| Oscillation mixing angles must be small like the quark mixing angles | Wrong |
| Solar neutrino oscillations must be small mixing angle MSW solution because it is “cool” | Wrong |
| Atmospheric neutrino anomaly must be other physics or experimental problem because it needs such a large mixing angle | Wrong |
| LSND result doesn’t fit in so must not be an oscillation signal | ????
Current Situation

Solar Neutrino Oscillations
- Deficit of $\nu_e$ observed from Sun Cl (Homestake), H$_2$O ((Super-)K), Ga (GALLEX, SAGE)
- Confirmation at SNO and KamLAND (reactor $\bar{\nu}_e$)

Atmospheric Neutrino Oscillations
- Zenith angle-dependent deficit of $\nu_\mu$: Kamioka, Super-Kamiokande, Soudan, MACRO
- Confirmed by accelerator exp K2K; MINOS will be definitive

LSND Neutrino Oscillations
- Excess of $\bar{\nu}_e$ in $\bar{\nu}_\mu$ beam produced from $\mu^+$ decay-at-rest
- Unconfirmed by other experiments, but not excluded
Three Signal Regions

- \( \mathbf{P}(\nu_\alpha \rightarrow \nu_\alpha) = 1 - \sin^2 2\theta \sin^2[1.27 \Delta m^2(L/E)] \)
- LSND:
  \( \Delta m^2 \approx 0.1 - 10 \text{ eV}^2 \), small mixing
- Atmospheric:
  \( \Delta m^2 \approx 2 \times 10^{-3} \text{ eV}^2 \), \( \sin^2 2\theta \approx 1.0 \)
- Solar:
  \( \Delta m^2 \approx 7 \times 10^{-5} \text{ eV}^2 \), \( \sin^2 2\theta \approx 0.8 \)

- Three distinct neutrino oscillation signals, with: \( \Delta m^2_{\text{sol}} + \Delta m^2_{\text{atm}} \neq \Delta m^2_{\text{LSND}} \)

- For three neutrinos, expect: \( \Delta m^2_{21} + \Delta m^2_{32} = \Delta m^2_{31} \! \) !
How Can There Be Three Distinct $\Delta m^2$?

• One of the experimental measurements is wrong

• One of the experimental measurements is not neutrino oscillations
  – Neutrino decay
  – Neutrino production from flavor violating decays

• Additional “sterile” neutrinos involved in oscillations

• CPT violation (or CP viol. and sterile $\nu$'s) allows different mixing for $\nu$'s and $\bar{\nu}$'s
The LSND Experiment

The neutrino source:

- $\bar{\nu}_\mu$ from: $\pi^+ \rightarrow \mu^+ \nu_\mu \leftrightarrow e^+ \nu_e \bar{\nu}_\mu$
- $E_\nu = 20-53$ MeV, $L_\nu = 25-35$ m
- Almost no $\bar{\nu}_e$ at source

The detector:

- Liquid scintillator detects both Cherenkov and scintillation light. For $\bar{\nu}_e p \rightarrow e^+ n$:
  - Č±-scintillation light from $e^+$
  - Scintillation light from $n$ capture
LSND Result

- Excess of candidate $\bar{\nu}_e$ events
- $R_\gamma$ parameter defines likelihood that $\gamma$ is correlated to $e^+$. By fitting $R_\gamma$:
  - $87.9 \pm 22.4 \pm 6.0$ excess ($3.8\sigma$)
  - $\langle P(\bar{\nu}_\mu \rightarrow \bar{\nu}_e) \rangle = (0.264 \pm 0.067 \pm 0.045)\%$
- Clean sample with $R_\gamma > 10$ cut
- $L_\nu/E_\nu$ distribution of the excess agrees well with oscillation hypothesis
- Backgrounds in green, red
- Fit to oscillation hypothesis in blue
KARMEN Experiment

• Similar beam and detector to LSND
  – Closer distance and less target mass
    ⇒ x10 less sensitive than LSND
• Joint analysis with LSND gives restricted region (Church et al. hep-ex/0203023)

• KARMEN also limits $\mu^+ \rightarrow e^+ \bar{\nu}_e \nu$ branching ratio:
  BR < 0.9 x 10^{-3} (90% CL)
• LSND signal would require:
  $1.9 \times 10^{-3} <$ BR < $4.0 \times 10^{-3}$ (90% CL)

  ⇒ $\mu^+ \rightarrow e^+ \bar{\nu}_e \nu$ unlikely to explain LSND signal

(also will be investigated by TWIST exp. at TRIUMF)
Adding Sterile Neutrinos to the Mix

- Reconcile three separate $\Delta m^2$ by adding additional sterile $\nu$'s

3+1 models

3+2 models

Constraints from atmos. and solar data

$\Rightarrow$ Sterile mainly associated with the LSND $\Delta m^2$

Then these are the main mixing matrix elements

3+1
3+2
3+3 Models

\[
\begin{pmatrix}
\nu_e \\
\nu_\mu \\
\nu_\tau \\
\nu_s \\
\nu_s' \\
\vdots
\end{pmatrix}
= 
\begin{pmatrix}
U_{e1} & U_{e2} & U_{e3} \\
U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\
U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \\
U_{s1} & U_{s2} & U_{s3} \\
U_{s'1} & U_{s'2} & U_{s'3} \\
\vdots & \vdots & \vdots
\end{pmatrix}
\begin{pmatrix}
\nu_1 \\
\nu_2 \\
\nu_3 \\
\nu_4 \\
\nu_5 \\
\vdots
\end{pmatrix}
\]
Also Proposals for Sterile $\nu$'s in Solar Spectrum

- Sterile neutrino component in the solar oscillation phenomenology
  Smirnov et al. hep-ph/0307266
  - Proposed to explain:
    1. Observed Ar rate is $2\sigma$ lower than predictions (LMA MSW)
    2. The lack of an upturn at low energies for the SNO and Super-K solar measurements

- Explain with a light sterile
  - $\Delta m^2 \sim (0.2 \text{ to } 2) \times 10^{-5} \text{ eV}^2$
  - $\sin^2 2\alpha \sim (10^{-5} \text{ to } 10^{-3})$

\[
R_\Delta \equiv \frac{\Delta m^2_{01}}{\Delta m^2_{21}}
\]
Sterile $\nu$'s and the r-process in Supernovae

- Heavy element ($A>100$) production in supernova (i.e. U) through rapid-neutron-capture (r-process)
  (i.e. Patel & Fuller hep-ph/0003034)

  - Observed abundance of heavy elements
    - Much larger than standard model prediction since available neutron density is too small

  - Required neutron density can be explained if oscillations to sterile neutrinos
    - Then matter effects can suppress the $\nu_e$ with respect to $\bar{\nu}_e$ which can then produce a substantial neutron excess

\[ \bar{\nu}_e + p \leftrightarrow e^+ + n, \ \nu_e + n \rightarrow e^- + p \]

\[ Y_e = 1/(1+(n/p)) \]
(Y_e small has neutron excess)
Sterile Neutrinos: Astrophysics Constraints

- Constraints on the number of neutrinos from BBN and CMB
  - Standard model gives $N_\nu = 2.6 \pm 0.4$ constraint
  - If $^4$He systematics larger, then $N_\nu = 4.0 \pm 2.5$
  - If neutrino lepton asymmetry or non-equilibrium, then the BBN limit can be evaded.
    K. Abazajian hep-ph/0307266
    G. Steigman hep-ph/0309347
  - “One result of this is that the LSND result is not yet ruled out by cosmological observations.”
    Hannestad astro-ph/0303076

- Bounds on the neutrino masses also depend on the number of neutrinos (active and sterile)
  - Allowed $\sum m_i$ is 1.4 (2.5) eV
    4 (5) neutrinos

\[ \begin{array}{ccc}
\text{N}_\nu = 3 & \text{solid} & \text{N}_\nu = 4 & \text{dotted} & \text{N}_\nu = 5 & \text{dashed} \\
\end{array} \]

Hannestad astro-ph/0303076
The Experimental Situation:
Fits of 3+1 and 3+2 Models to Data

- Global Fits to high $\Delta m^2$ oscillations for the SBL experiments including LSND positive signal.  

<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>
</tr>
</thead>
<tbody>
<tr>
<td>$\nu_\mu \to \nu_e$</td>
<td>LSND</td>
<td>$3 \cdot 10^{-2}$</td>
<td>$&gt; 2.5 \cdot 10^{-3}$</td>
</tr>
<tr>
<td></td>
<td>KARMEN</td>
<td>$6 \cdot 10^{-2}$</td>
<td>$&lt; 1.7 \cdot 10^{-3}$</td>
</tr>
<tr>
<td></td>
<td>NOMAD</td>
<td>$4 \cdot 10^{-1}$</td>
<td>$&lt; 1.4 \cdot 10^{-3}$</td>
</tr>
<tr>
<td>$\nu_e \to \nu_\mu$</td>
<td>Bugey</td>
<td>$1 \cdot 10^{-2}$</td>
<td>$&lt; 1.4 \cdot 10^{-1}$</td>
</tr>
<tr>
<td></td>
<td>CHOOZ</td>
<td>$7 \cdot 10^{-4}$</td>
<td>$&lt; 1.0 \cdot 10^{-1}$</td>
</tr>
<tr>
<td>$\nu_\mu \to \nu_\mu$</td>
<td>CCFR84</td>
<td>$6 \cdot 10^0$</td>
<td>none</td>
</tr>
<tr>
<td></td>
<td>CDHS</td>
<td>$3 \cdot 10^{-1}$</td>
<td>none</td>
</tr>
<tr>
<td>$\nu_\mu \to \nu_\tau$</td>
<td>NOMAD</td>
<td>$7 \cdot 10^{-1}$</td>
<td>$&lt; 3.3 \cdot 10^{-4}$</td>
</tr>
<tr>
<td></td>
<td>CHORUS</td>
<td>$5 \cdot 10^{-1}$</td>
<td>$&lt; 6.8 \cdot 10^{-4}$</td>
</tr>
<tr>
<td>$\nu_e \to \nu_\tau$</td>
<td>NOMAD</td>
<td>$6 \cdot 10^0$</td>
<td>$&lt; 1.5 \cdot 10^{-2}$</td>
</tr>
<tr>
<td></td>
<td>CHORUS</td>
<td>$7 \cdot 10^0$</td>
<td>$&lt; 5.1 \cdot 10^{-2}$</td>
</tr>
</tbody>
</table>

- Only LSND has a positive signal
  - CDHS near detector 2$\sigma$ low also contributes

- Is LSND consistent with the upper limits on active to sterile mixing derived from the null short-baseline experiments?  
3 + 1 Model Fits to SBL Data

\( P(\bar{\nu}_\mu \rightarrow \bar{\nu}_e) = 4U_{e4}^2 U_{\mu4}^2 \sin^2(1.27\Delta m_{41}^2 L/E) \)

LSND allowed regions compared to Null short-baseline exclusions

- Doing a combined fit with null SBL and the positive LSND results
  - Yields compatible regions at the 90% CL

Best fit: \( \Delta m^2 = 0.92 \text{ eV}^2 \), \( U_{e4} = 0.136 \), \( U_{\mu4} = 0.205 \)

Best Compatibility Level = \(~3.6\%\)
Combined LSND and NSBL Fits to 3+2 Models

\[ P(\bar{\nu}_\mu \rightarrow \bar{\nu}_e) = 4(U_{e4}U_{\mu4} + U_{e5}U_{\mu5}) (U_{e4}U_{\mu4} \sin^2 \theta_{41} + U_{e5}U_{\mu5} \sin^2 \theta_{51}) - 4U_{e4}U_{\mu4}U_{e5}U_{\mu5} \sin^2 \theta_{54} \]

\[ x_{ji} = 1.27 \Delta m_{ji}^2 L/E \]

- **Confidence Levels:**
  - 3+1 \( \Rightarrow \) 3.6% compatibility
  - 3+2 \( \Rightarrow \) 30% compatibility

Best Fit: \( \Delta m_{41}^2 = 0.92 \text{ eV}^2 \), \( U_{e4} = 0.121 \), \( U_{\mu4} = 0.204 \), \( \Delta m_{51}^2 = 22 \text{ eV}^2 \), \( U_{e5} = 0.036 \), \( U_{\mu4} = 0.224 \)

\[ p_{LSND} \equiv \langle P(\bar{\nu}_\mu \rightarrow \bar{\nu}_e) \rangle_{LSND} \]

CP Violation in 3+2 Models

- CP-violation is possible when more than one $\Delta m^2$ participates in the oscillation.

- For (3+2) models:

$$P(\bar{\nu}_\mu \rightarrow \bar{\nu}_e) = 4|U_{e4}|^2|U_{\mu 4}|^2 \sin^2 x_{41} + 4|U_{e5}|^2|U_{\mu 5}|^2 \sin^2 x_{51} +$$

$$+ 8|U_{e4}||U_{\mu 4}||U_{e5}||U_{\mu 5}| \sin x_{41} \sin x_{51} \cos(x_{54} \pm \phi_{54})$$

$$x_{ji} \equiv 1.27 \Delta m^2_{ji} L/E, \quad \phi_{54} \equiv \arg(U^*_{e4}U_{\mu 4}U_{e5}U^*_{\mu 5})$$

- The SBL CP-violating phase, $\phi_{54}$, is different from the “standard” CP phase $\delta$:
  
  - $\phi_{54}$ is associated with $\Delta m^2_{41}$, $\Delta m^2_{51}$
  - $\delta$ is associated with $\Delta m^2_{21}$, $\Delta m^2_{31}$
CP Violating Effects for MiniBooNE

- Compare oscillation probabilities in $\nu$ and $\bar{\nu}$ running mode:

  \[ p_{\text{BooNE}} \equiv \langle P(\nu_\mu \rightarrow \nu_e) \rangle_{\nu} \text{ mode}, \quad \bar{p}_{\text{BooNE}} \equiv \langle P(\nu_\mu \rightarrow \bar{\nu}_e) \rangle_{\nu} \text{ mode} \]

- Asymmetry, based on (3+2) models allowed by present SBL constraints

(M. Sorel and K. Whisnant, preliminary)
Next Step is MiniBooNE

• *MiniBooNE will be one of the first experiments to check these sterile neutrino models*
  
  – Investigate LSND Anomaly
    • *Is it oscillations?*
    • *Measure the oscillation parameters*
  
  – Investigate oscillations to sterile neutrino using $\nu_\mu$ disappearance
MiniBooNE Experiment

12m sphere filled with mineral oil and PMTs located 500m from source

Use protons from the 8 GeV booster ⇒ Neutrino Beam $<E_{\nu} > \sim 1$ GeV
MiniBooNE Collaboration

Y. Liu, I. Stancu  Alabama
S. Koutsoliotas  Bucknell
E. Hawker, R.A. Johnson, J.L. Raaf  Cincinnati
T. Hart, R.H. Nelson, E.D. Zimmerman  Colorado
D. Smith  Embry Riddle
D. C. Cox, A. Green, H.-O. Meyer, R. Tayloe  Indiana
R. Imlay, W. Metcalf, M. Sung, M.O. Wascko  Louisiana State
J. Cao, Y. Liu, B.P. Roe, H. Yang  Michigan
A.O. Bazarko, P.D. Meyers, R.B. Patterson, F.C. Shoemaker, H.A. Tanaka  Princeton

MiniBooNE consists of about 70 scientists from 12 institutions.
MiniBooNE Neutrino Beam

Variable decay pipe length (2 absorbers @ 50m and 25m)

8 GeV Proton Beam Transport

50m Decay Pipe

Magnetic Horn

MiniBooNE Neutrino Beam

8 GeV Proton Beam Transport

Fermilab
8 GeV Booster

target & horn

decay pipe
\[ \pi \rightarrow \mu \nu \]
25 or 50 m

absorber

450 m of dirt

detector

One magnetic Horn, with Be target

Magnetic Horn

Detector
Horn, Target & Fluxes

- **8 GeV Protons impinge on 71cm long Be target**
- Horn focusing of secondary beam increase \(\nu\) flux by factor of \(~5\)
- **170 kA pulses, 143\(\mu\)s long at \(~5\) Hz**
- Has performed flawlessly with \(~80\) million pulses to date

- Main \(\nu_\mu\) flux from \(\pi^+ \rightarrow \mu^+ \nu_\mu\)
- Intrinsic \(\nu_e\) flux from
  - \(\mu^+ \rightarrow \nu_\mu \, e^+ \nu_e\)
  - \(K^+ \rightarrow \pi^0 \, e^+ \nu_e\)
  - \(K^0_L \rightarrow \pi^- \, e^+ \nu_e\)
The MiniBooNE Detector

- 12 meter diameter sphere
- Filled with 950,000 liters (900 tons) of very pure mineral oil
- Light tight inner region with 1280 photomultiplier tubes
- Outer veto region with 241 PMTs.

Oscillation Search Method:
Look for $\nu_e$ events in a pure $\nu_\mu$ beam
Particle Identification

- Separation of $\nu_\mu$ from $\nu_e$ events
  -Exiting $\nu_\mu$ events fire the veto
  -Stopping $\nu_\mu$ events have a Michel electron after a few $\mu$sec
  -Also, scintillation light with longer time constant $\Rightarrow$ enhanced for slow pions and protons
  -Čerenkov rings from outgoing particles
    -Shows up as a ring of hits in the phototubes mounted inside the MiniBooNE sphere
    -Pattern of phototube hits tells the particle type
Examples of Real Data Events

**Charged Current**
\[ \nu_\mu + n \rightarrow \mu^- + p \]
with outgoing muon (1 ring)

**Neutral Current**
\[ \nu_\mu + n \rightarrow \nu_\mu + \pi^0 + p \]
with outgoing \(\pi^0 \rightarrow \gamma \gamma \) (2 rings)
Example Cerenkov Rings

Size of ring is proportional to the light hitting the photomultiplier tube

\[ \nu_\mu + n \rightarrow \mu^- + p \]

\[ \nu_\mu + n \rightarrow \nu_\mu + p + \pi^0 \]

\[ \pi^0 \rightarrow \gamma + \gamma \]
Muon Identification
Signature:
\[ \mu \rightarrow e \, \nu_\mu \, \nu_e \]
after \(~2\mu\text{sec}\)

**Animation**
Each frame is 25 ns with 10 ns steps.

**Charge (Size)**
- Low
- High

**Time (Color)**
- Early
- Late
Neutrino events

beam comes in spills @ up to 5 Hz
each spill lasts 1.6 µsec

trigger on signal from Booster
read out for 19.2 µsec; beam at [4.6, 6.2] µsec

no high level analysis needed to see
neutrino events

backgrounds: cosmic muons
decay electrons

simple cuts reduce non-beam
backgrounds to ~10^{-3}

ν event every 1.5 minutes

Current Collected data:
300k neutrino candidates
for 2.8 x 10^{20} protons on target
Fine Beam Event Timing

- A resistive wall monitor measures the beam time profile just before the target
- Discriminated signal sent to DAQ for fine timing

With ...
- Fitted event position
- Fitted event time
- RWM timing pulse

we measure the booster bunch timing....

in neutrinos!
Reconstruction: Event Position

- Fitted position of the centre of the event track
- Cuts:-
  - Tank hits > 200
  - Veto hits < 6
  - Fit radius < 500cm
- Cartesian coordinates scaled to give equal volume slices in a sphere

Asymmetry from anisotropy of event directions + veto cut

Rolloff at edges from veto cut
Energy Calibration Checks

- Spectrum of Michel electrons from stopping muons

![Graph showing spectrum of Michel electrons](image)

- Energy vs. Range for events stopping in scintillator cubes

![Graph showing energy vs. range](image)

- Mass distribution for isolated $\pi^0$ events

![Graph showing mass distribution](image)
Neutrino Energy Reconstruction

For quasi-elastic events (\( \nu_{\mu} + n \rightarrow \mu^- + p \) and \( \nu_e + n \rightarrow e^- + p \))

\[ \Rightarrow \text{Can use kinematics to find } E_\nu \text{ from } E_{\mu(e)} \text{ and } \theta_{\mu(e)} \]

\[ E_{\nu}^{QE} = \frac{2ME_i - m_i^2}{2(M - E_i + P_i \cos \theta_e)} \]

Energy Resolution vs. \( \nu_{\mu} \) Energy

Monte Carlo \( \nu_{\mu} + n \rightarrow \mu^- + p \)

\[ \frac{\Delta E_{\nu}^a}{E_{\nu}^{Gen}} = a^2 + \left( \frac{b}{E_{\nu}^{Gen}} \right)^2 + \left( \frac{c}{E_{\nu}^{Gen}} \right)^3 \]

- \( a = 3.788008e-02 \)
- \( b = 8.364264e-02 \)
- \( c = 0.000000e+00 \)

\( 10\% \)

Monte Carlo \( \nu_e + n \rightarrow e^- + p \)

\( 10\% \)
Oscillation Analysis: Status and Plans

• Blind (or “Closed Box”) $\nu_e$ appearance analysis
  you can see all of the info on some events
  or
  some of the info on all events
  but
  you cannot see all of the info on all of the events

• Other analysis topics give early interesting physics results and serve as a cross check and calibration before “opening the $\nu_e$ box”
  – $\nu_\mu$ disappearance oscillation search
  – Cross section measurements for low-energy $\nu$ processes
  – Studies of $\nu_\mu$ NC $\pi^0$ production
    ⇒ coherent (nucleus) vs nucleon
  – Studies of $\nu_\mu$ NC elastic scattering
    ⇒ Measurements of $\Delta s$ (strange quark spin contribution)
Low Energy Neutrino Cross sections

CC $\nu_\mu$ Total Cross Sections

$\nu_\mu n \rightarrow \mu^- p$

CC $\nu_\mu$ Quasi–Elastic Cross Section

$\sigma(\nu_\mu N \rightarrow \mu X)/E(\text{GeV})$ (10$^{-38}$ cm$^2$ GeV$^{-1}$)

$E_\nu$ (GeV)

$\sigma(\nu_\mu \rightarrow \mu^- p)$ (10$^{-38}$ cm$^2$)

$E_\nu$ (GeV)

MiniBooNE

NUX

NUANCE

NEUGEN

TOTAL

QE

DIS

Single Pion


ANL. Barish, Phys. Rev. D16, 3103 (1977), D2


SKAT. Brunner, Z. Phys. C45, 551 (1990), CF$_3$Br


C$F_3$Br

NUANCE (free nucleon)

$M_\nu = 0.84$ GeV, $M_\pi = 1.0$ GeV

NUANCE (nucleon bound in $^{12}$C)
On the Road to a $\nu_\mu$ Disappearance Result

- **Use $\nu_\mu$ quasi-elastic events**
  \[ \nu_\mu + n \rightarrow \mu^- + p \]
  - Events can be isolated using single ring topology and hit timing
  - Excellent energy resolution
  - High statistics: ~30,000 events now (Full sample: ~500,000)

- **$E_\nu$ distribution well understood from pion production by 8 GeV protons**
  - Sensitivity to $\nu_\mu \rightarrow \nu_\mu$ disappearance oscillations through shape of $E_\nu$ distribution

Monte Carlo estimate of final sensitivity

Will be able to cover a large portion of 3+1 models
Estimates for the $\nu_\mu \rightarrow \nu_e$ Appearance Search

- Look for appearance of $\nu_e$ events above background expectation
  - Use data measurements both internal and external to constrain background rates

- Fit to $E_\nu$ distribution used to separate background from signal.

![Pie chart showing event types and percentages]

![Histograms showing signal, misidentification, and intrinsic $\nu_e$ events]
Intrinsic $\nu_e$ in the beam

Small intrinsic $\nu_e$ rate $\Rightarrow$ Event Ratio $\nu_e/\nu_\mu=6\times10^{-3}$

$\pi^+ \rightarrow \mu^+ \nu_\mu \quad \leftarrow e^+ \nu_e \nu_\mu$

$\nu_e$ from $\mu$–decay
- Directly tied to the observed half-million $\nu_\mu$ interactions

$K^+ \rightarrow \pi^0 e^+ \nu_e$

$K_L \rightarrow \pi^- e^+ \nu_e$

Kaon rates measured in low energy proton production experiments
- HARP experiment (CERN)
- E910 (Brookhaven)

"Little Muon Counter" measures rate of kaons in-situ

- Directly tied to the observed half-million $\nu_\mu$ interactions

Monte Carlo

Kaon rates measured in low energy proton production experiments
- HARP experiment (CERN)
- E910 (Brookhaven)

"Little Muon Counter" measures rate of kaons in-situ
Mis-identification Backgrounds

- Background mainly from NC $\pi^0$ production
  
  $$\nu_\mu + p \rightarrow \nu_\mu + p + \pi^0$$
  followed by
  
  $$\pi^0 \rightarrow \gamma \gamma$$
  where one $\gamma$ is lost because it is too low energy

- Over 99.5% of these events are identified and the $\pi^0$ kinematics are measured
  
  $\Rightarrow$ Can constrain this background directly from the observed data
MiniBooNE Oscillation Sensitivity

- Oscillation sensitivity and measurement capability
  - Data sample corresponding to $1 \times 10^{21}$ pot
  - Systematic errors on the backgrounds average \~5\%

\[ \Delta m^2 = 0.4 \text{ eV}^2 \]
\[ \Delta m^2 = 1 \text{ eV}^2 \]
Run Plan

• At the current time have collected $2.8 \times 10^{20}$ p.o.t.
  – Data collection rate is steadily improving as the Booster accelerator losses are reduced
  – Many improvement being implemented into the Booster and Linac (these not only help MiniBooNE but also the Tevatron and NuMI in the future)

• Plan is to “open the $\nu_e$ appearance box” when the analysis has been substantiated and when sufficient data has been collected for a definitive result
  \[ \Rightarrow \text{Current estimate is sometime in 2005} \]

• Which then leads to the question of the next step
  – If MiniBooNE sees no indications of oscillations with $\nu_\mu$
    \[ \Rightarrow \text{Need to run with $\bar{\nu}_\mu$ since LSND signal was $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$} \]
  – If MiniBooNE sees an oscillation signal
    \[ \Rightarrow \text{Then ............} \]
Experimental Program with Sterile Neutrinos

If sterile neutrinos then many mixing angles, CP phases, and $\Delta m^2$ to include

- Measure number of extra masses $\Delta m_{14}^2$, $\Delta m_{15}^2$ ...

- Measure mixings
  Could be many small angles

\[
\begin{pmatrix}
\nu_e \\
\nu_\mu \\
\nu_\tau \\
\nu_s \\
\nu_s' \\
\vdots
\end{pmatrix} = 
\begin{pmatrix}
U_{e1} & U_{e2} & U_{e3} & U_{e4} & U_{e5} & \cdots \\
U_{\mu 1} & U_{\mu 2} & U_{\mu 3} & U_{\mu 4} & U_{\mu 5} \\
U_{\tau 1} & U_{\tau 2} & U_{\tau 3} & U_{\tau 4} & U_{\tau 5} \\
U_{s 1} & U_{s 2} & U_{s 3} & U_{s 4} & U_{s 5} \\
U_{s' 1} & U_{s' 2} & U_{s' 3} & U_{s' 4} & U_{s' 5} \\
\vdots & \vdots & \vdots & \vdots & \vdots
\end{pmatrix} \begin{pmatrix}
\nu_1 \\
\nu_2 \\
\nu_3 \\
\nu_4 \\
\nu_5 \\
\vdots
\end{pmatrix}
\]

- Oscillations to sterile neutrinos could effect long-baseline measurements and strategy

- Compare $\nu_\mu$ and $\bar{\nu}_\mu$ oscillations $\Rightarrow$ CP and CPT violations
Next Step: BooNE: Two (or Three) Detector Exp.

- Far detector at 2 km for low $\Delta m^2$ or 0.25 km for high $\Delta m^2$ ⇐ BooNE
- Near detector at ~100m (Finesse Proposal) for disappearance and precision background determination

- Precision measurement of oscillation parameters
  - $\sin^22\theta$ and $\Delta m^2$
  - Map out the nxn mixing matrix

- Determine how many high mass $\Delta m^2$ 's
  - 3+1, 3+2, 3+3 ............

- Show the L/E oscillation dependence
  - Oscillations or $\nu$ decay or ???

- Explore disappearance measurement in high $\Delta m^2$ region
  - Probe oscillations to sterile neutrinos

(These exp’s could be done at FNAL, BNL, JPARC)
If MiniBooNE sees $\nu_\mu \rightarrow \nu_e$ (or not) then:
Run BooNE with anti-neutrinos for $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$

- Direct comparison with LSND
- Are $\nu_\mu$ and $\bar{\nu}_\mu$ the same?
  - Mixing angles, $\Delta m^2$ values
- Explore CP (or CPT) violation by comparing $\nu_\mu$ and $\bar{\nu}_\mu$ results
- Running with antineutrinos takes about x2 longer to obtain similar sensitivity
Probing the CP-phase with MiniBooNE

(M. Sorel and K. Whisnant, preliminary)

- Present SBL constraints allow for all possible CP-phase values
- Large ($\simeq 50\%$) differences in MiniBooNE $\nu/\bar{\nu}$ running mode results are possible, and might be measurable $\Rightarrow$ establish $(3+n)$ models and measure $\phi_{54}$?

**Fix masses and mixings**

\[
\Delta m^2_{21} = 0.92 \text{eV}^2, \quad U_{e4} = 0.12, \quad U_{\mu 4} = 0.20 \\
\Delta m^2_{31} = 2.2 \text{eV}^2, \quad U_{e5} = 0.04, \quad U_{\mu 5} = 0.22
\]

\[p_{\text{BooNE}} = \langle P(\nu_\mu \rightarrow \nu_e) \rangle_{\nu \text{ mode}}, \quad \bar{p}_{\text{BooNE}} = \langle P(\bar{\nu}_\mu \rightarrow \bar{\nu}_e) \rangle_{\bar{\nu} \text{ mode}}
\]
Effect of LSND Signal on Offaxis Exps.

An LSND-like oscillation can show up in off-axis experiments as an unexpected $\nu_e$ appearance signal

- If this signal is not understood in both $\nu$ and $\bar{\nu}$ modes
  $\Rightarrow$ Can affect ability to measure CP violation effects.
Another Next Step:

Do $\nu_\mu \rightarrow \nu_\tau$ Appearance Experiment at High $\Delta m^2$

- Appearance of $\nu_\tau$ would help sort out the mixings through the sterile components

- Need moderately high neutrino energy to get above the 3.5 GeV $\tau$ threshold (~6-10 GeV)

- Example: NuMI Med energy beam 8 GeV with detector at L=2km (116m deep)
Conclusions

• Neutrinos have been surprising us for some time and will most likely continue to do so.

• Although the “neutrino standard model” can be used as a guide, the future direction for the field is going to be determined by what we discover from experiments.

• Sterile neutrinos may open up a whole $\nu$ area to explore.