MiniBooNE Antineutrino Oscillation Results and Implications for the Future

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Outline

- LSND $\nu_\mu \rightarrow \nu_e$ Oscillation Results
- MiniBooNE $\nu_\mu \rightarrow \nu_e$ Oscillation Search
- MiniBooNE $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ Oscillation Search
- Fits to the World Antineutrino Data
- Testing LSND/MiniBooNE Signals with Future Experiments
- Conclusion
LSND Signal

- LSND experiment
- Stopped pion beam
  \[ \pi^+ \rightarrow \mu^+ + \nu_\mu \]
  \[ \rightarrow e^+ + \bar{\nu}_\mu + \nu_e \]
- Excess of \( \bar{\nu}_e \) in \( \bar{\nu}_\mu \) beam
- \( \bar{\nu}_e \) signature: Cherenkov light from \( e^+ \) with delayed \( \gamma \) from n-capture
- Excess = 87.9 ± 22.4 ± 6 (3.8σ)
LSND Signal

- Assuming two neutrino oscillations

\[ P(\bar{\nu}_\mu \rightarrow \bar{\nu}_e) = \sin^2(2\theta) \sin^2 \left( \frac{1.27 L \Delta m^2}{E} \right) = 0.245 \pm 0.067 \pm 0.045 \% \]

- Can't reconcile LSND result with atmospheric and solar neutrino using only 3 Standard Model neutrinos – only two independent mass splittings
Sterile Neutrinos

- 3+N models

- For N>1, model allows CP violation for short baseline
  - \( \nu_\mu \rightarrow \nu_e \neq \bar{\nu}_\mu \rightarrow \bar{\nu}_e \)

\[ \Delta m_{45}^2 \sim 0.1 \text{ – } 100 \text{ eV}^2 \]
\[ \Delta m_{34}^2 \sim 0.1 \text{ – } 100 \text{ eV}^2 \]
MiniBooNE Experiment

- Similar L/E as LSND
  - MiniBooNE ~500m/~500MeV
  - LSND ~30m/~30MeV
- Horn focused neutrino beam (p+Be)
  - Horn polarity $\rightarrow$ neutrino or anti-neutrino mode
- 800t mineral oil Cherenkov detector
$\nu_e$ Event Rate Predictions

$\#\text{Events} = \text{Flux} \times \text{Cross-sections} \times \text{Detector response}$

- **External measurements**
  - (HARP, E910, etc)
  - $\nu_\mu$ rate constrained by neutrino data

- **External and MiniBooNE measurements**
  - $-\pi^0$, delta and dirt backgrounds constrained from data.

- **Detailed detector simulations checked with neutrino data and calibration sources.**

**Neutrino**

<table>
<thead>
<tr>
<th>Color</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Green</td>
<td>Effective $\pi^0$'s</td>
</tr>
<tr>
<td>Blue</td>
<td>Dirt</td>
</tr>
<tr>
<td>Pink</td>
<td>Delta's</td>
</tr>
<tr>
<td>Yellow</td>
<td>Other</td>
</tr>
<tr>
<td>Lt Blue</td>
<td>Nue (CCQE)</td>
</tr>
</tbody>
</table>

**Antineutrino**

<table>
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<td>Lt Blue</td>
<td>Nue (CCQE)</td>
</tr>
</tbody>
</table>
Neutrino Flux from GEANT4 Simulation

Wrong-sign background is \(~6\%\) for Nu-Mode & \(~18\%\) for Antinu-Mode
Intrinsic $\nu_e$ background is \(~0.5\%\) for both Nu-Mode & Antinu-Mode
Neutrino Cross Sections

NUANCE

NC EL

CC π⁺
NuInt07, final results soon

QE

multi-π

NC π⁰

NC π⁺⁻
CC π⁰
PAC (Mar 2008)
**NC π^0** Scattering


**coherent fraction=19.5+-1.1+-2.5%**
**ν_μ CCQE Scattering**


Fermi Gas Model describes CCQE ν_μ data well

\[ M_A = 1.23 \pm 0.20 \text{ GeV} \]
\[ \kappa = 1.019 \pm 0.011 \]

Also used to model ν_e and ν_e̅ interactions

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From Q^2 fits to MB ν_μ CCQE data:

- \( M_{A_{\text{eff}}} \) -- effective axial mass
- \( \kappa \) -- Pauli Blocking parameter

From electron scattering data:

- \( E_b \) -- binding energy
- \( p_f \) -- Fermi momentum

---

Fermi Gas Model describes CCQE ν_μ data well

186000 muon neutrino events

14000 anti-muon neutrinos

PRELIMINARY
$n_\mu$ CCQE Scattering


Extremely surprising result - CCQE $\sigma_{n_\mu}^{(12C)}>6 \sigma_{n_\mu}(n)$

How can this be? Not seen before, requires correlations. Fermi Gas has no correlations and should be an overestimate.

MiniBooNE Neutrino Oscillation Results
A.A. Aguilar-Arevalo et al., PRL 102, 101802 (2009)

- 6.5e20 POT
- No excess of events in signal region (E>475 MeV)
- Inconsistent with simple 2ν oscillations as explanation of LSND (assuming no CP violation)
MiniBooNE Neutrino Oscillation Results
A.A. Aguilar-Arevalo et al., PRL 102, 101802 (2009)

Excess of events observed at low energy:
128.8 ± 20.4 ± 38.3 (3.0σ)
Shape not consistent with simple 2ν oscillations
Magnitude consistent with LSND


Lorentz Violation: Katori, Kostelecky, & Tayloe, Phys. Rev. D74 (2006) 105009


MiniBooNE Data Show a Low-Energy Excess

A.A. Aguilar-Arevalo et al., PRL 102, 101802 (2009)

Excess from 200-475 MeV = 128.8±20.4±38.3 events

6.46E20 POT
Low-Energy Excess vs $\cos \theta$
MiniBooNE Antineutrino Oscillation Results

- $5.66 \times 10^{20} \text{ POT}$
MiniBooNE Antineutrino Null Probability

- Absolute $\chi^2$ probability of null point (background only) - model independent
- Frequentist approach

<table>
<thead>
<tr>
<th>Energy Range (MeV)</th>
<th>$\chi^2$/NDF</th>
<th>Probability</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\nu_\mu \rightarrow \nu_e$</td>
<td>6.1/6</td>
<td>40%</td>
</tr>
<tr>
<td>$\bar{\nu}_\mu \rightarrow \bar{\nu}_e$</td>
<td>18.5/6</td>
<td>0.5%</td>
</tr>
</tbody>
</table>

![Graph showing excess events vs. $E_{QE}$ (GeV)]
MiniBooNE Oscillation Fit E>475

- 5.66E20 POT
- E>475 is signal region for LSND type osc.
- Oscillations favored over background only hypotheses at 99.4% CL (model dependent)
- Best fit \((\sin^2 2\theta, \Delta m^2) = (0.9584, 0.064 \text{ eV}^2)\)
  \[\chi^2/\text{NDF} = 8.0/4; \text{Prob.} = 8.7\% \ (475-1250 \text{ MeV})\]
$\Delta \chi^2$ vs $\Delta m^2$

(Best $\Delta \chi^2$ at each $\Delta m^2$)
MiniBooNE
Oscillation Fit

$E > 475$ MeV

$\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ oscillation results appear to confirm the LSND evidence for antineutrino oscillations, although more data are needed.
MiniBooNE Oscillation Fit

$E > 200$ MeV

$\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ oscillation results appear to confirm the LSND evidence for antineutrino oscillations, although more data are needed.
3+1 Global Fit to World Antineutrino Data (with new MiniBooNE data set)

Updated from
G. Karagiorgi et al.,
PRD80, 073001
(2009)

Best 3+1 Fit:
$\Delta m_{41}^2 = 0.92 \text{ eV}^2$
$\sin^2 2\theta_{\mu\mu} = 0.0045$
$\chi^2 = 85.0/103 \text{ DOF}$
Prob. = 90%

Predicts $\bar{\nu}_\mu$ & $\bar{\nu}_e$
disappearance of
$\sin^2 2\theta_{\mu\mu} \sim 37\%$ and
$\sin^2 2\theta_{ee} \sim 4.3\%$
3+N Models Requires Large $\bar{\nu}_\mu$ Disappearance!

In general, $P(\bar{\nu}_\mu \rightarrow \bar{\nu}_e) < \frac{1}{4} P(\bar{\nu}_\mu \rightarrow \bar{\nu}_x) P(\bar{\nu}_e \rightarrow \bar{\nu}_x)$

Reactor Experiments: $P(\bar{\nu}_e \rightarrow \bar{\nu}_x) < 5\%$

LSND/MiniBooNE: $P(\bar{\nu}_\mu \rightarrow \bar{\nu}_e) \sim 0.25\%$

Therefore: $P(\bar{\nu}_\mu \rightarrow \bar{\nu}_x) > 20\%$

(Assuming the light neutrinos are mostly active and the heavy neutrinos are mostly sterile.)
Improved results soon from MiniBooNE/SciBooNE Joint Analysis!
Initial MINOS $\bar{\nu}_\mu$ Disappearance Results in $\nu$ Mode

Expect $\bar{\nu}_\mu$ disappearance above 10 GeV for LSND neutrino oscillations.
Initial MINOS $\nu_\mu$ Disappearance Results in $\nu$ Mode

Expect $\nu_\mu$ disappearance above 10 GeV for LSND neutrino oscillations.
Future Experiments

- More MiniBooNE $\overline{\nu}$ Data (15E20 POT)

- MicroBooNE
  - CD1 approved
  - Address low energy excess

- Few ideas under consideration: (talk by Mills)
  - Move or build a MiniBooNE like detector at 200m (LOI arXiv:0910.2698)
  - A new search for anomalous neutrino oscillations at the CERN-PS (arxiv:0909.0355v3)
  - Redoing a stopped pion source at ORNL (OscSNS - http://physics.calumet.purdue.edu/~oscsns/)
More MiniBooNE Antineutrino Running
MicroBooNE sensitivity to low energy excess:
(neutrino running,
70 ton fiducial volume,
x2 higher PID efficiency than MiniBooNE,
3% mis-ID,
6.0e20 POT)

Electron-like hypothesis:
36.8 excess events
41.6 background events
5.7σ stat. significance

Photon-like hypothesis:
36.8 excess events
78.9 background events
4.1σ stat. significance
Conclusions

• The MiniBooNE data are consistent with $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ oscillations at $\Delta m^2 \sim 1$ eV$^2$ and consistent with the evidence for antineutrino oscillations from LSND.

• The MiniBooNE $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ oscillation allowed region appears to be different from the $\nu_\mu \rightarrow \nu_e$ oscillation allowed region. (CP Violation?)

• The world antineutrino data fit well to a 3+1 oscillation model with $\Delta m^2 \sim 1$ eV$^2$. All 3+N models predict large $\bar{\nu}_\mu$ disappearance.

• Future Experiments (BooNE at FNAL, ICARUS at CERN, or OscSNS at ORNL) could measure neutrino oscillations with high significance ($>5\sigma$) and prove that sterile neutrinos exist!
Backup
3+1 Global Fit to World Antineutrino Data (with new MiniBooNE data set)

Updated from G. Karagiorgi et al., PRD80, 073001 (2009)

Best 3+1 Fit:
\[ \Delta m_{41}^2 = 0.92 \text{ eV}^2 \]
\[ \sin^2 2\theta_{\mu e} = 0.0045 \]
\[ \chi^2 = 85.0/103 \text{ DOF} \]
Prob. = 90%

Predicts $\overline{\nu}_\mu$ & $\overline{\nu}_e$ disappearance of
\[ \sin^2 2\theta_{\mu\mu} \sim 37\% \text{ and} \]
\[ \sin^2 2\theta_{ee} \sim 4.3\% \]
3+1 Global Fit to World Antineutrino Data (with old MiniBooNE data set)

Best 3+1 Fit:
\[ \Delta m_{41}^2 = 0.915 \text{ eV}^2 \]
\[ \sin^2 2\theta_{\mu e} = 0.0043 \]
\[ \chi^2 = 87.9/103 \text{ DOF} \]
Prob. = 86%

Predicts \( \bar{\nu}_\mu \) & \( \bar{\nu}_e \) disappearance of
\[ \sin^2 2\theta_{\mu\mu} \sim 35\% \] and
\[ \sin^2 2\theta_{ee} \sim 4.3\% \]
The MiniBooNE Detector

- 541 meters downstream of target
- 3 meter overburden
- 12.2 meter diameter sphere
  (10 meter “fiducial” volume)
- Filled with 800 t
  of pure mineral oil (CH$_2$)
  (Fiducial volume: 450 t)
- 1280 inner phototubes,
  240 veto phototubes
- Simulated with a GEANT3 Monte Carlo
10% Photocathode coverage

Two types of Hamamatsu Tubes: R1408, R5912

Charge Resolution: 1.4 PE, 0.5 PE

Time Resolution: 1.7 ns, 1.1 ns
Rejecting “muon-like” events

Using $\log(L_e/L_\mu)$

$log(L_e/L_\mu)>0$ favors electron-like hypothesis

Note: photon conversions are electron-like. This does not separate $e/\pi^0$.

Separation is clean at high energies where muon-like events are long.

Analysis cut was chosen to maximize the $\nu_\mu \rightarrow \nu_e$ sensitivity
Testing $e$-$\pi^0$ separation using data

1 subevent
log($L_e/L_\mu$) > 0 (e-like)
log($L_e/L_\pi$) < 0 (π-like)
mass > 50 (high mass)
The most important types of neutrino events in the oscillation search:

**Background Muons (or charged pions):**
Produced in most CC events. Usually 2 or more subevents or exiting through veto.

**Signal and Background Electrons (or single photon):**
Tag for $\nu_\mu \rightarrow \nu_e$ CCQE signal. 1 subevent

**Background $\pi^0$s:**
Can form a background if one photon is weak or exits tank. In NC case, 1 subevent.
Joint LSND/KARMEN Analysis

Joint analysis with Karmen2: 64% compatible

E. Church, et al., PRD 66, 013001
LSND $\bar{\nu}_e$ Background Estimates

<table>
<thead>
<tr>
<th>Estimate</th>
<th>$\bar{\nu}<em>e/\nu</em>\mu$</th>
<th>$\bar{\nu}_e$ Bkgd</th>
<th>LSND Excess</th>
</tr>
</thead>
<tbody>
<tr>
<td>LSND Paper</td>
<td>0.086%</td>
<td>19.5+-3.9</td>
<td>87.9+-22.4+-6.0</td>
</tr>
<tr>
<td>Zhemchugov Poster1</td>
<td>0.071%</td>
<td>16.1+-3.2</td>
<td>91.3+-22.4+-5.6</td>
</tr>
<tr>
<td>Zhemchugov Poster2</td>
<td>0.092%</td>
<td>20.9+-4.2</td>
<td>86.5+-22.4+-6.2</td>
</tr>
<tr>
<td>Zhemchugov Seminar</td>
<td>0.119%</td>
<td>27.0+-5.4</td>
<td>80.4+-22.4+-7.1</td>
</tr>
</tbody>
</table>

All $\bar{\nu}_e$ background estimates assume a 20% error. Note that the $\bar{\nu}_e/\nu_\mu$ ratio determines the background!

LSND Paper: A. Aguilar et al., Phys. Rev. D 64, 112007 (2001); (uses MCNP)

Zhemchugov Poster1: **FLUKA** $\bar{\nu}_e/\nu_\mu$ ratio presented at the ICHEP 2010 Conference, Paris

Zhemchugov Poster2: **GEANT4** $\bar{\nu}_e/\nu_\mu$ ratio presented at the ICHEP 2010 Conference, Paris

Zhemchugov Seminar: **FLUKA** $\bar{\nu}_e/\nu_\mu$ ratio presented at CERN on September 14, 2010

Although the analysis of Zhemchugov et al. is not fully understood or endorsed, their $\bar{\nu}_e/\nu_\mu$ ratios agree reasonably well with the published LSND results.

Note that LSND measures the correct rate of $\bar{\nu}_\mu \ p \rightarrow \mu^+ \ n$ interactions, which confirms the $\pi^-$ production and background estimates. Note also, that FLUKA & GEANT4 are not as reliable as MCNP at 800 MeV!
Backgrounds: Order $\left( G^2 \alpha \alpha_s \right)$, single $\gamma$ FS?

Other PCAC

So far no one has found a NC process to account for the $\nu, \bar{\nu}$ difference & the $\nu$ low-energy excess. Work is in progress:

R. Hill, arXiv:0905.0291
Jenkins & Goldman, arXiv:0906.0984
Sterile $\nu$ Decay?

- The decay of a ~50 MeV sterile $\nu$ has been shown to accommodate the LSND & MiniBooNE excesses
  - Gninenko, PRL 103, 241802 (2009)
  - arXiv:1009.5536
More Complicated $\nu$ Oscillations?

3+1 Global Fit to World Neutrino Data Only


Best 3+1 Fit:
$\Delta m_{41}^2 = 0.19 \text{ eV}^2$
$\sin^2 2\theta_{\mu e} = 0.031$
$\chi^2 = 90.5/90 \text{ DOF}$
Prob. = 46%

Predicts $\nu_\mu$ & $\nu_e$
disappearance of
$\sin^2 2\theta_{\mu\mu} \sim 3.1\%$ and
$\sin^2 2\theta_{ee} \sim 3.4\%$
Neutrino Oscillations

Weak Eigenstates

\[ \nu_\mu \quad = \quad \cos \theta \nu_1 + \sin \theta \nu_2 \]
\[ \nu_e \quad = \quad -\sin \theta \nu_1 + \cos \theta \nu_2 \]

Eigenstates of Propagation

\[ P(\nu_\mu) \]
\[ P(\nu_e) \]

\[ P_{\nu_\mu \rightarrow \nu_e} = \sin^2(2\theta) \sin^2(1.27 \Delta m^2 L/E_\nu) \]

\[ \Delta m^2 = m_2^2 - m_1^2 \text{ in eV}^2, \quad L \text{ in meters, } E_\nu \text{ in MeV} \]
Probability of Neutrino Oscillations

\[ P_{\alpha \beta} = \delta_{\alpha \beta} - 4 \sum_i \sum_j |U_{\alpha i} U_{\beta i}^* U_{\alpha j} U_{\beta j}^*| \sin^2(1.27 \Delta m_{ij}^2 L/E_\nu) \]

As N increases, the formalism gets rapidly more complicated!

<table>
<thead>
<tr>
<th>N</th>
<th>#\Delta m_{ij}^2</th>
<th>#\theta_{ij}</th>
<th>#CP Phases</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>1</td>
<td>1</td>
<td>0</td>
</tr>
<tr>
<td>3</td>
<td>2</td>
<td>3</td>
<td>1</td>
</tr>
<tr>
<td>6</td>
<td>5</td>
<td>15</td>
<td>10</td>
</tr>
</tbody>
</table>
T & CP & CPT Violation in the Lepton Sector

\[ \nu_\alpha \rightarrow \nu_\beta \neq \nu_\beta \rightarrow \nu_\alpha \quad \text{T Violation} \]
\[ \nu_\alpha \rightarrow \nu_\beta \neq \bar{\nu}_\alpha \rightarrow \bar{\nu}_\beta \quad \text{CP Violation} \]
\[ \nu_\alpha \rightarrow \nu_\beta \neq \bar{\nu}_\beta \rightarrow \bar{\nu}_\alpha \quad \text{CPT Violation} \]
Cosmology Data Consistent with Extra Sterile Neutrinos (J. Hamann, et. al. arXiv:1006.5276)

\[ 3 + N_s \]
\[ m_\nu = 0 \]

\[ 3 + N_s \]
\[ m_s = 0 \]
Modeling Production of Secondary Pions

- HARP (CERN)
  - 5% $\lambda$ Beryllium target
  - 8.9 GeV proton beam momentum
  - $\pi^+$ & $\pi^-$

Data are fit to a Sanford-Wang parameterization.

HARP collaboration, hep-ex/0702024
Calibration Sources

Tracker system

15% E resolution at 53 MeV

Michel electrons

δm~20%

π^0

Michel electron distribution (absolute calibration)

π^0 photon energies

Tracker & Cubes

Through-going cosmics

Visible energy range of oscillation signal

Visible Tank Energy (MeV)

Cosmic Muon Energy

Cube Range Energy (MeV)

Monte Carlo

Data
# Number of Excess Events

<table>
<thead>
<tr>
<th>Energy (MeV)</th>
<th>Data</th>
<th>Background</th>
<th>Excess</th>
<th>$\sigma_{\text{tot}}$ ($\sigma_{\text{stat}}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>200-300</td>
<td>232</td>
<td>186.8+-26.0</td>
<td>45.2+-13.7+-22.1</td>
<td>1.7 (3.3)</td>
</tr>
<tr>
<td>300-475</td>
<td>312</td>
<td>228.3+-24.5</td>
<td>83.7+-15.1+-19.3</td>
<td>3.4 (5.5)</td>
</tr>
<tr>
<td>200-475</td>
<td>544</td>
<td>415.2+-43.4</td>
<td>128.8+-20.4+-38.3</td>
<td>3.0 (6.3)</td>
</tr>
<tr>
<td>475-1250</td>
<td>408</td>
<td>385.9+-35.7</td>
<td>22.1+-19.6+-29.8</td>
<td>0.6 (1.1)</td>
</tr>
<tr>
<td>200-1250</td>
<td>952</td>
<td>801.0+-58.1</td>
<td>151.0+-28.3+-50.7</td>
<td>2.6 (5.3)</td>
</tr>
</tbody>
</table>
## Number of Excess Events

<table>
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<tr>
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<th>Data</th>
<th>Background</th>
<th>Excess</th>
<th>#σ_{tot} (#σ_{stat})</th>
</tr>
</thead>
<tbody>
<tr>
<td>200-475</td>
<td>119</td>
<td>100.5+-14.3</td>
<td>18.5+-10.0+-10.2</td>
<td>1.3 (1.9)</td>
</tr>
<tr>
<td>475-675</td>
<td>64</td>
<td>38.3+-7.2</td>
<td>25.7+-6.2+-3.7</td>
<td>3.6 (4.1)</td>
</tr>
<tr>
<td>475-1250</td>
<td>120</td>
<td>99.1+-14.0</td>
<td>20.9+-10.0+-9.8</td>
<td>1.5 (2.1)</td>
</tr>
<tr>
<td>475-3000</td>
<td>158</td>
<td>133.3+-18.0</td>
<td>24.7+-11.5+-13.8</td>
<td>1.4 (2.1)</td>
</tr>
<tr>
<td>200-3000</td>
<td>277</td>
<td>233.8+-22.5</td>
<td>43.2+-15.3+-16.5</td>
<td>1.9 (2.8)</td>
</tr>
</tbody>
</table>
LSND/MiniBooNE Data Compared to 3+N Global Fits

(3+1) $\nu_\mu$ Model Antineutrino Appearance

3+1

(3+2) $\nu_b \nu_\mu$ Model Antineutrino Appearance

3+2
3+2 Global Fit to the World $\nu$ & $\bar{\nu}$ Data

One light sterile $\nu$ (0.1 - 20 eV) &
one heavy sterile $\nu$ (33 eV – 40 GeV)