Short Baseline Neutrino Oscillations

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Standard Model & Neutrino Oscillations

- 3 neutrinos
  - Initially assumed massless
- Mixing matrix:

\[
\begin{pmatrix}
\nu_e \\
\nu_\mu \\
\nu_\tau
\end{pmatrix} =
U_{e1} \begin{pmatrix}
U_{e1} & U_{e2} & U_{e3}
\end{pmatrix}
\begin{pmatrix}
\nu_1 \\
\nu_2 \\
\nu_3
\end{pmatrix}
\]

- Oscillation Probability:

\[
P_{\alpha\beta} = \left| \langle \nu_\beta | \nu_\alpha(t) \rangle \right|^2 = \delta_{\alpha\beta} - 4 \sum_{i<j}^n \text{Re}[U_{\alpha i} U_{\beta i}^* U_{\alpha j} U_{\beta j}] \sin^2 X_{ij}
\]

\[
+ 2 \sum_{i<j}^n \text{Im}[U_{\alpha i} U_{\beta i}^* U_{\alpha j} U_{\beta j}] \sin 2X_{ij}
\]

\[
X_{ij} = \frac{(m_i^2 - m_j^2) L}{4E} = 1.27 \frac{\Delta m_{ij}^2}{eV^2} \frac{L}{m/\text{MeV}}
\]
Neutrino Oscillations

- Lot of experimental evidence
- L/E dependence
- Precise measurement of atmospheric and solar $\Delta m^2$

\[ \Delta m_{32}^2 \equiv m_3^2 - m_2^2 \]

\[ \Delta m_{21}^2 \equiv m_2^2 - m_1^2 \]
- Evidence for oscillations at higher $\Delta m^2$ than atmospheric and solar
- Stopped pion beam
  \[ \pi^+ \rightarrow \mu^+ + \nu_\mu \to e^+ + \nu_\mu + \nu_e \]
- Excess of $\bar{\nu}_e$ in $\bar{\nu}_\mu$ beam
- $\bar{\nu}_e$ signature: Cherenkov light from $e^+$ with delayed $n$-capture
- Excess=87.9 $\pm$ 22.4 $\pm$ 6 (3.8$\sigma$)
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

\[
\Delta m^2_{32} \equiv m_3^2 - m_2^2
\]

\[
\Delta m^2_{21} \equiv m_2^2 - m_1^2
\]
Sterile neutrinos

- 3 active neutrinos + 1 sterile neutrino
- Sterile neutrino has no Standard Model interactions
- Active neutrinos can oscillate into sterile
- 3 parameters relevant for short baseline exp.: $\Delta m_{41}^2$, $|U_{e4}|$ and $|U_{\mu 4}|$

\[
P(\nu_\mu \rightarrow \nu_e) = 4 |U_{e4}|^2 |U_{\mu 4}|^2 \sin^2 (1.27 \Delta m_{41}^2 L/E)
\]
\[
P(\nu_e \rightarrow \nu_e) = 1 - 4 |U_{e4}|^2 \left( 1 - |U_{e4}|^2 \right) \sin^2 (1.27 \Delta m_{41}^2 L/E)
\]
\[
P(\nu_\mu \rightarrow \nu_\mu) = 1 - 4 |U_{\mu 4}|^2 \left( 1 - |U_{\mu 4}|^2 \right) \sin^2 (1.27 \Delta m_{41}^2 L/E)
\]
More sterile neutrinos

- Next minimal extension 3+2 models
- Favored by fits to world data
- Model allows CP violation
  - $\nu_\mu \rightarrow \nu_e \neq \overline{\nu}_\mu \rightarrow \overline{\nu}_e$

$\Delta m^2_{34} \sim 0.1 - 100 \text{ eV}^2$
MiniBooNE experiment

- Similar L/E as LSND
  - MiniBooNE ~500m/~500MeV
  - LSND ~30m/~30MeV
- Horn focused neutrino beam (p+Be)
  - Horn polarity → neutrino or anti-neutrino mode
- 800t mineral oil Cherenkov detector
Predicted neutrino flux

- Neutrino mode
  - $\nu_\mu$ 93.6%
  - $\overline{\nu}_\mu$ 5.8%
  - $\nu_e + \overline{\nu}_e$ 0.6%

- Anti-neutrino mode
  - $\nu_\mu$ 15.7%
  - $\overline{\nu}_\mu$ 83.7%
  - $\nu_e + \overline{\nu}_e$ 0.6%

*Phys. Rev. D79, 072002 (2009)*
MiniBooNE neutrino result

- 6.5e20 Protons On Target (POT)
- No excess of events in fit region (E>475 MeV)
- Disfavors LSND 2ν oscillation explanation for neutrinos (assuming no CP or CPT violation)

*Phys. Rev. Lett. 98, 231801 (2007)*
MiniBooNE neutrino result

Excess of events observed at low energy:
$128.8 \pm 20.4 \pm 38.3 \ (3.0\sigma)$
Shape not consistent with 2 $\nu$ oscillations
Magnitude consistent with LSND

Anomaly Mediated Neutrino-Photon Interactions at Finite Baryon Density:


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


New Gauge Boson with Sterile Neutrinos:
New $\bar{\nu}_e$ appearance results

- Updated analysis with 8.58E20 POT - ~50% more data
- Nearly same analysis as before
  - New constraint on nue flux from K+ decays using SciBooNE + fit to K+ production global data (1105.2871, accepted by Phys. Rev. D)

<table>
<thead>
<tr>
<th></th>
<th>200-475MeV</th>
<th>475-1250MeV</th>
</tr>
</thead>
<tbody>
<tr>
<td>Data</td>
<td>189</td>
<td>168</td>
</tr>
<tr>
<td>MC</td>
<td>150.4±18.5</td>
<td>151.7±19.4</td>
</tr>
<tr>
<td>Excess</td>
<td>38.6±18.5</td>
<td>16.3±19.4</td>
</tr>
<tr>
<td>LSND Best Fit</td>
<td>11.4</td>
<td>33.3</td>
</tr>
<tr>
<td>Expectation from $\nu$ low E excess</td>
<td>17</td>
<td>0</td>
</tr>
<tr>
<td>LSND+Low E</td>
<td>28.4</td>
<td>33.3</td>
</tr>
</tbody>
</table>
Fit $E > 475$ MeV

- $8.58 \times 10^{20}$ POT
- $E > 475$ is neutrino mode fit region
- Oscillations favored over background only hypotheses at 91.4% CL
- Probability:
  
  \[
  P(\text{null}) = 14.9\% \\
  P(\text{Best Fit}) = 35.5\%
  \]
E$\geq$200MeV

- E<475MeV:
  - Larger background & systematics
- Oscillations favored over background only hypotheses at 97.6% CL (model dependent)
- No assumption made about low energy excess
- p(null)=10.1%
  p(BF) = 50.7%
E≥200MeV

- E<475MeV:
  - Larger background & systematics

- Oscillations favored over background only hypotheses at 94.2% CL (model dependent)

- Subtract low energy excess assuming neutrinos anti-neutrino mode contribute to the excess (17 events)

- p(null)=28.3%
  p(BF) =76.5%
LSND vs MB direct comparison
Reactor antineutrino anomaly

- Recent re-evaluation of reactor fluxes $\rightarrow +3\%$
- Observed/predicted event rate $= 0.943 \pm 0.023$
- Deviation from unity at 98.6% CL

*Phys. Rev. D 83, 073006 (2011)*
Gallium Anomaly

- GALLEX and SAGE calibration runs with intense MCi sources ($\nu_e$)
- Neutrinos detected through radiochemical counting of Ge nuclei: $^{71}\text{Ga} + \nu_e \rightarrow ^{71}\text{Ge} + e^-$
  - 2 runs at GALLEX with $^{51}\text{Cr}$ source ($\sim 750$ keV)
  - 1 run at SAGE with $^{51}\text{Cr}$ source
  - 1 run at SAGE with $^{37}\text{Ar}$ source ($\sim 810$ keV)
- All runs observed deficit of neutrino interactions compared to the expected activity
  - $R = \text{meas}/\text{pred} = 0.86 \pm 0.06$

*Phys.Rev.D 83, 073006 (2011)*
Sterile neutrinos?

- Reactor data and GALLEX/SAGE
- Data consistent with sterile neutrino oscillations
- Null disfavored at 99.8%
- High $\Delta m^2$ excluded by limits on nue disappearance using KARMEN and LSND (arxiv:1106.5552)

\[
\sin^2(2\theta) = 0.14 \pm 0.07
\]
\[
\Delta m^2 > 1.5\text{eV}^2 @ 99\% \text{CL}
\]

Cosmology

- Data consistent with extra sterile neutrinos
- $N_s = \text{number of thermalized sterile neutrinos}$

*Phys. Rev. Lett. 105, 181301 (2010)*
3+N models require large $\bar{\nu}_\mu$ disappearance

- In general:
  \[ P(\bar{\nu}_\mu \rightarrow \bar{\nu}_e) < \frac{1}{4} P(\bar{\nu}_\mu \rightarrow \bar{\nu}_x) P(\bar{\nu}_e \rightarrow \bar{\nu}_x) \]

- From reactor experiments:
  \[ P(\bar{\nu}_e \rightarrow \bar{\nu}_x) < 8\% \]

- From LSND/MiniBooNE:
  \[ P(\bar{\nu}_\mu \rightarrow \bar{\nu}_e) \sim 0.25\% \]

- Therefore:
  \[ P(\bar{\nu}_\mu \rightarrow \bar{\nu}_x) > 10\% \]

*Assuming light neutrinos are mostly active and sterile neutrinos are heavy*
\( \nu_\mu \) disappearance

- Provides a constraint on \( \nu_e \) appearance
- Combined SciBooNE-MiniBooNE analysis in neutrino mode
- MiniBooNE only in anti-neutrino mode

*arxiv:1106.5685

*Phys.Rev.Lett.103:061802,2009*
MINOS $\nu_\mu$ vs $\bar{\nu}_\mu$

- Hint of NSI or CPT violation?

Future outlook

- MiniBooNE – more antineutrino data, approved to run through spring 2012
- Joint MiniBooNE/SciBooNE $\nu_\mu$ disappearance
- MicroBooNE - resolve the low energy excess
- MINOS+ - sterile neutrinos, NSI, …

- BooNE
- Stopped pion source exp. (OscSNS,...)
- Icarus at CERN-PS
Conclusion

- MiniBooNE anti neutrino data consistent with LSND and $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ oscillations at $\Delta m^2 \sim 1 eV^2$

- Few other hints of sterile neutrinos – reactor anomaly, gallium anomaly, cosmology

- Very active topic:
  - Workshop on Sterile Neutrinos and on the Reactor (anti)-Neutrino Anomaly, TUM, Garching, Feb 8 2011
  - Beyond3nu, Gran Saso, May 3-4 2011
  - Short Baseline Neutrino Workshop, Fermilab, May 12-14 2011
  - Sterile Neutrinos At The Crossroads, Virginia Tech, Sep 26-28 2011
Backup slides
2+2

- Within 2+2 model Sterile neutrino participates in either solar or atmospheric neutrino oscillations (or both)
- Experiments measuring solar and atmospheric $\Delta m_{34}^2 \sim 0.1 - 100 \text{ eV}^2$ disfavor oscillations to pure sterile neutrinos

$\Rightarrow$ 2+2 is strongly disfavored
Future sensitivity

- Potential exclusion of null point assuming best fit signal

- Combined analysis of $\nu_e$ and $\bar{\nu}_e$
BooNE

- MiniBooNE like detector at 200m
- Flux, cross section and optical model errors cancel in 200m/500m ratio analysis
- Present neutrino low energy excess is 6 sigma statistical; 3 sigma when include systematics
- Study L/E dependence
- Gain statistics quickly, already have far detector data
BooNE

- Better sensitivity to $\nu_\mu$ ($\bar{\nu}_\mu$) disappearance
- Look for CPT violation ($\nu_\mu \rightarrow \nu_\mu \neq \bar{\nu}_\mu \rightarrow \bar{\nu}_\mu$)
OscSNS

• Spallation neutron source at ORNL
• 1GeV protons on Hg target (1.4MW)
• Free source of neutrinos
• Well understood flux of neutrinos
OscSNS

- $\bar{\nu}_e$ appearance (left) and $\nu_\mu$ disappearance sensitivity (right) for 1 year of running
## LSND $\bar{\nu}_e$ Background Estimates

<table>
<thead>
<tr>
<th>Estimate</th>
<th>$\bar{\nu}<em>e/\bar{\nu}</em>\mu$</th>
<th>$\nu_e$ 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 Poster</td>
<td>0.071%</td>
<td>16.1+-3.2</td>
<td>91.3+-22.4+-5.6</td>
</tr>
<tr>
<td>Dydak Seminar</td>
<td>0.116%</td>
<td>26.3+-5.3</td>
<td>81.1+-22.4+-7.0</td>
</tr>
</tbody>
</table>

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

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

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

Dydak Seminar: **FLUKA**$\bar{\nu}_e/\bar{\nu}_\mu$ ratio presented at FNAL on January 14, 2011

Although the analysis of Zhemchugov, Dydak et al. is not fully understood or endorsed, their $\bar{\nu}_e/\bar{\nu}_\mu$ 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 overestimate $\pi^-$ production at ~800 MeV. Note that $N_{gs}$ events are included in the LSND background estimate.
GEANT4 Overestimates $\pi^-$ Production!

$p (730 \text{ MeV}) + C: 45^\circ \pi^-$ spectrum

$p (730 \text{ MeV}) + C: 60^\circ \pi^-$ spectrum
\( \nu_\text{e} \text{ C} \rightarrow \text{e}^- \text{N}_{\text{gs}} \) Events Do Not Simulate
\( \bar{\nu}_\text{e} \text{ p} \rightarrow \text{e}^+ \text{n} \) Events!

For \( \text{N}_{\text{gs}} \) \( \beta \) decay to be considered a 2.2 MeV \( \gamma \):
\( \Delta r<2m, \Delta t<500\mu s, 19<N_{\text{hits}}<51 \)

The number of \( \text{N}_{\text{gs}} \) events with a \( \beta \) that satisfies this initial
requirement is approximately: \((600)(1)(1/31.8)(0.05) \sim 1 \) event.

The number of \( \text{N}_{\text{gs}} \) events with \( R_\gamma>10 \sim 0.1 \) events.

This background is included in the LSND background estimate.