Sterile neutrinos

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What is ν?
Invisibles 2012 and Alexei Smirnov Fest

GGI, Firenze, Italy – June 28th, 2012

I. The LSND experiment and four-neutrino models
II. MiniBooNE and models with two sterile neutrinos
III. A word on MiniBooNE data after Neutrino 2012

Summary
I. The LSND experiment and four-neutrino models

The LSND problem

- LSND observed $\bar{\nu}_e$ appearance in a $\bar{\nu}_\mu$ beam ($E_\nu \sim 30$ MeV, $L \simeq 35$ m);
- Karmen did not confirm the claim, but couldn’t fully exclude it either;
- the signal is compatible with $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ oscillations provided that $\Delta m^2 \gtrsim 0.1$ eV$^2$;
- on the other hand, other data give (at $3\sigma$):
  \[ \Delta m^2_{\text{sol}} \approx 7.5 \pm 0.6 \times 10^{-5} \text{ eV}^2, \]
  \[ |\Delta m^2_{\text{atm}}| \approx 2.4 \pm 0.3 \times 10^{-3} \text{ eV}^2; \]
- in order to explain LSND with mass-induced neutrino oscillations one needs at least one more neutrino mass eigenstate;
- **WARNING**: having enough $\Delta m^2$ is not enough. To make sure that the model works, one has to check explicitly that all the experiments can be fitted simultaneously.
I. The LSND experiment and four-neutrino models

Four neutrino mass models

- Approximation: $\Delta m^2_{\text{SOL}} \ll \Delta m^2_{\text{ATM}} \ll \Delta m^2_{\text{LSND}} \Rightarrow 6$ different mass schemes:

- Total: $3 \Delta m^2$, $6$ angles, $3$ phases. Different set of experimental data partially decouple:
I. The LSND experiment and four-neutrino models

(2+2): ruled out by solar and atmospheric data

- in (2+2) models, fractions of $\nu_s$ in solar ($\eta_s$) and atmos ($1 - d_s$) add to one $\Rightarrow \eta_s = d_s$;
- $3\sigma$ allowed regions $\eta_s \leq 0.31$ (solar) and $d_s \geq 0.63$ (atmos) do not overlap; superposition occurs only above $4.5\sigma$ ($\chi^2_{PC} = 19.9$);
- the $\chi^2$ increase from the combination of solar and atmos data is $\chi^2_{PG} = 28.6$ (1 dof), corresponding to a PG = $9 \times 10^{-8}$ \cite{1}.

\[1\] M. Maltoni, T. Schwetz, M.A. Tortola, J.W.F. Valle, Nucl. Phys. B643 (2002) 321 [hep-ph/0207157].

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I. The LSND experiment and four-neutrino models

(3+1): tension between LSND and short-baseline data

- In (3+1) schemes the SBL appearance probability is effectively $2\nu$ oscillations:

$$P_{\mu e} = \sin^2 2\theta \sin^2 \frac{\Delta m^2_{41} L}{4E}, \quad \sin^2 2\theta = 4 |U_{e4}|^2 |U_{\mu 4}|^2;$$

- disappearance experiments bound $|U_{e4}|^2$ and $|U_{\mu 4}|^2$;

- LSND is in conflict [1]:
  - with other appearance experiments (Karmen & Nomad);
  - with all disappearance exp’s.

[1] M. Maltoni, T. Schwetz, M.A. Tortola, J.W.F. Valle, Nucl. Phys. B643 (2002) 321 [hep-ph/0207157].

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The MiniBooNE experiment (≤ 5/2012)

- $E_\nu$ and $L$ very different from LSND (but similar $L/E_\nu$)
  ⇒ can check the oscillation solution of the LSND problem, not the signal itself;
- very peculiar results:
  - strong low-energy excess in $\nu_e$, mild in $\bar{\nu}_e$;
  - mild mid-energy excess in $\bar{\nu}_e$, but not in $\nu_e$.

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**LSND vs MiniBooNE in (3+1)**

- $\nu_e$: no signal $\Rightarrow$ **excludes** LSND;
- $\bar{\nu}_e$: signal $\Rightarrow$ **mildly confirms** LSND.

![Graph showing the comparison between LSND and MiniBooNE in the (3+1) neutrino framework.](image)

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Status of (3+1) models after MiniBooNE

- (3+1) four-neutrino schemes fail because:
  - can’t reconcile appearance and disappearance data;
  - can’t explain the different $\nu_e$ (MB) and $\bar{\nu}_e$ (LSND) results;
  - can’t account for the low-energy $\nu_e$ event excess in MB.

$\Rightarrow$ (3+1) models are ruled out as explanation of SBL data.

[2] G. Karagiorgi et al., Phys. Rev. D80 (2009) 073001 [arXiv:0906.1997].

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• MiniBooNE observed a $3.0\sigma$ excess at low-$E$ [3];
• this excess is incompatible with $2\nu$ oscillations;
• therefore, data with $E_{\nu}^{QE} < 475$ MeV have not been used to check LSND.

⇒ Omission of low-energy bins in based on the hypothesis of two-flavor oscillations!
• Is it possible to do something about these data in more sophisticated models?

[3] A.A. Aguilar-Arevalo et al.[MiniBooNE collab], Phys. Rev. Lett. 98 (2007) 231801 [arXiv:0704.1500].

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Explaining the MiniBooNE excess with two sterile neutrinos

• With one extra sterile neutrino, $m_4$:

$$P_{\mu e}^{4\nu} = 4|U_{e4}|^2|U_{\mu 4}|^2 \sin^2 \phi_{41} \quad \text{with} \quad \phi_{ij} \equiv \frac{\Delta m_{ij}^2 L}{4E};$$

• for large energy $P_{\mu e}^{4\nu}$ drops as $1/E^2$;

• however, the low-energy MB excess is much sharper ($\sim 1/E^4$);

⇒ it is not possible to account for the MB excess with only one extra sterile neutrino.

• On the other hand, with two extra neutrinos, $m_4$ and $m_5$:

$$P_{\mu e}^{5\nu} = 4|U_{e4}|^2|U_{\mu 4}|^2 \sin^2 \phi_{41} + 4|U_{e5}|^2|U_{\mu 5}|^2 \sin^2 \phi_{51} + 8|U_{e4} U_{e5} U_{\mu 4} U_{\mu 5}| \sin \phi_{41} \sin \phi_{51} \cos(\phi_{54} - \delta);$$

• terms of order $1/E^2$ cancel if $\delta = \pi$ and $|U_{e4} U_{\mu 4}| \Delta m_{41}^2 = |U_{e5} U_{\mu 5}| \Delta m_{51}^2$;

⇒ with two extra sterile states it is possible to fit the MB low-energy excess [4].

[4] M. Maltoni, T. Schwetz, Phys. Rev. D76 (2007) 093005 [arXiv:0705.0107].
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Reconciling MiniBooNE and LSND in (3+2) models

- **Trick**: use the CP phase $\delta = \arg(U_{e4}^* U_{\mu4} U_{e5} U_{\mu5}^*)$ to differentiate $\nu$ (MB) from $\bar{\nu}$ (LSND):

  $$ P^{5\nu}_{\mu e} = 4|U_{e4}|^2 |U_{\mu4}|^2 \sin^2 \phi_{41} + 4|U_{e5}|^2 |U_{\mu5}|^2 \sin^2 \phi_{51} + 8|U_{e4} U_{e5} U_{\mu4} U_{\mu5}| \sin \phi_{41} \sin \phi_{51} \cos(\phi_{54} - \delta) ; $$

- note that $\delta = \pi + \epsilon$ and $|U_{e4} U_{\mu4}| \Delta m_{41}^2 \approx |U_{e5} U_{\mu5}| \Delta m_{51}^2$ to suppress MB probability [4].

[4] M. Maltoni, T. Schwetz, Phys. Rev. D76 (2007) 093005 [arXiv:0705.0107].

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Fitting all appearance data in (3+2) models

| data set         | $|U_{e4}U_{\mu4}|$ | $\Delta m^2_{41}$ | $|U_{e5}U_{\mu5}|$ | $\Delta m^2_{51}$ | $\delta$ | $\chi^2_{\text{min}}$/dof | gof |
|------------------|------------------|-----------------|-----------------|-----------------|---------|-----------------|-----|
| appearance (CPC) | 0.12             | 0.18            | 0.006           | 2.31            | –       | 95.8/86         | 22% |
| appearance (CPV) | 0.080            | 0.39            | 0.029           | 1.10            | $1.1\pi$ | 82.5/85         | 56% |

NOTE: data taken from Ref. [2], which uses old MB-\$\bar{\nu}\$ data.

[2] G. Karagiorgi et al., Phys. Rev. D80 (2009) 073001 [arXiv:0906.1997].

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**The doom of disappearance data**

- As for (3+1) models, disappearance data imply bounds on $|U_{ei}|^2$ and $|U_{\mu i}|^2$ ($i = 4, 5$);
- these bounds are in conflict with the large values of $|U_{ei}U_{\mu i}|$ required by appearance data;
- again, a tension between APP and DIS arises:

  $\chi^2_{PG} = 17.5$ (4 dof) $\Rightarrow$ PG = $1.5 \times 10^{-3}$ [no MB];

  $\chi^2_{PG} = 17.2$ (4 dof) $\Rightarrow$ PG = $1.8 \times 10^{-3}$ [MB475];

  $\chi^2_{PG} = 25.1$ (4 dof) $\Rightarrow$ PG = $4.8 \times 10^{-5}$ [MB300];

- alternatively, compare LSND and NEV as in (3+1):

  $\chi^2_{PG} = 19.6$ (5 dof) $\Rightarrow$ PG = $1.5 \times 10^{-3}$ [before MB];

  $\chi^2_{PG} = 21.2$ (5 dof) $\Rightarrow$ PG = $7.4 \times 10^{-4}$ [after MB].

$\Rightarrow$ Conclusion: (3+2) models fail exactly as (3+1) [4].

[4] M. Maltoni, T. Schwetz, Phys. Rev. D76 (2007) 093005 [arXiv:0705.0107].

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The reactor neutrino anomaly

- In [6, 7] the reactor $\bar{\nu}$ fluxes has been reevaluated;
- the new calculations result in a small increase of the flux by about 3.5%;
- hence, all reactor short-baseline (RSBL) exp. finding no evidence are actually observing a deficit;
- this deficit could be interpreted as being due to SBL neutrino oscillations;
- deficit independent of $L \Rightarrow \Delta m^2 \gtrsim 1 \text{ eV}^2$;
- impact on previous results:
  - $4\nu$: small ($4\nu$ dead anyway);
  - $5\nu$: important.

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[5] T. Schwetz, M. Tortola, J.W.F. Valle, New J. Phys. 13 (2011) 063004 [arXiv:1103.0734].
[6] T.A. Mueller et al., Phys. Rev. C83 (2011) 054615 [arXiv:1101.2663].
[7] P. Huber, Phys. Rev. C 84 (2011) 024617 [arXiv:1106.0687].
[8] G. Mention et al., Phys. Rev. D83 (2011) 073006 [arXiv:1101.2755].
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Can the reactor neutrino anomaly save the day?

- As expected, the new reactor fluxes lead to a clear preference for $|U_{e4}|^2 \neq 0$;
- however, the upper bound on $|U_{e4}|^2$ is not dramatically reduced;
- moreover, the bound on $|U_{\mu 4}|^2$ from atmospheric data is now independently confirmed by MINOS;
- all together, there is no reason to expect an impressive weakening of the disappearance bound.

[9] T. Schwetz, talk at Neutrino Conference, Kyoto, Japan, June 3-9, 2012.
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Impact of the new reactor fluxes

- (3+1) models: $\chi^2_{PG}/dof = 24.2/2 \rightarrow 21.5/2$ for LSND + MB($\bar{\nu}$) vs NEV ($\Delta\chi^2_{PG} = 2.7$);

- (3+2) models:
  \[
  \begin{cases}
  \chi^2_{PG}/dof = 25.1/5 \rightarrow 19.9/5 & \text{for LSND + MB($\bar{\nu}$) vs NEV ($\Delta\chi^2_{PG} = 5.2$);} \\
  \chi^2_{PG}/dof = 19.4/4 \rightarrow 14.7/4 & \text{for APP vs DIS ($\Delta\chi^2_{PG} = 4.7$).}
  \end{cases}
  \]

[10] J. Kopp, M. Maltoni and T. Schwetz, Phys. Rev. Lett. 107 (2011) 091801 [arXiv:1103.4570].

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**Status of (3+2) models with the new reactor fluxes**

- (3+2) models experience substantial improvement, but tension with disappearance data remains considerably strong: PG=0.53%;
- situation becomes more critical if the MiniBooNE low-E excess is included, since larger mixing angles are required;
- (1+3+1) works slightly better, but has stronger problems with cosmology since the sum of neutrino masses ($\sum m_\nu$) is larger.

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[10] J. Kopp, M. Maltoni and T. Schwetz, Phys. Rev. Lett. 107 (2011) 091801 [arXiv:1103.4570].

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III. A word on MiniBooNE data after Neutrino 2012

MiniBooNE: neutrino data

- No new data, but improved analysis. Full details: [→ Steve Brice’s talk];
- is $\nu$ signal compatible with $2\nu$ oscillations? \(\begin{align*}
2007: P_{\text{osc}} &\approx 1\% \Rightarrow \text{no it isn’t [3]}; \\
2012: P_{\text{osc}} &\approx 6\% \Rightarrow \text{maybe it is [11]};
\end{align*}\)
- do MB $\nu$ data rule out LSND $\bar{\nu}$ signal in (3+1)? 2007: yes [3]; 2012: not really [11].

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[3] A.A. Aguilar-Arevalo et al.[MiniBooNE collab], Phys. Rev. Lett. 98 (2007) 231801 [arXiv:0704.1500].

[11] C. Polly, talk at Neutrino Conference, Kyoto, Japan, June 3-9, 2012.

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MiniBooNE: antineutrino data

- New data presented at Neutrino 2012, statistics doubled [11];
- compatibility with $\nu$ data: \[
\left\{ \begin{array}{l}
\text{low-energy excess increased } \Rightarrow \text{better agreement;}
\text{mid-energy excess reduced } \Rightarrow \text{better agreement;}
\end{array} \right.
\]
- is $\bar{\nu}$ signal compatible with $2\nu$ oscillations? $P_{\text{osc}} = 67\% \Rightarrow \text{definitely yes}$ [11];
- is MB-$\bar{\nu}$ signal compatible with LSND? Yes, irrespective of the energy threshold.

[11] C. Polly, talk at Neutrino Conference, Kyoto, Japan, June 3-9, 2012.

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MiniBooNE: global $\nu + \bar{\nu}$ appearance analysis in (3+1)

- MiniBooNE $\nu$ and $\bar{\nu}$ no longer in open disagreement with LSND within (3+1) models;
- however, dramatic change in interpretation not linked to dramatic change in data;
- problems still there ($P_{\text{osc}} \simeq 6.7\%$ [11]) $\Rightarrow$ no great change expected in our conclusions.

[11] C. Polly, talk at Neutrino Conference, Kyoto, Japan, June 3-9, 2012.
A few experiments exhibit deviations from the “standard” $3\nu$ scenario:

- LSND observed an excess of $\bar{\nu}_e$ events in a $\bar{\nu}_\mu$ beam;
- MiniBooNE mildly “confirm” this excess: 
  \[
  \begin{cases} 
  \text{in both } \bar{\nu} \text{ mode and } \nu \text{ mode at low-E;} \\
  \text{only in } \bar{\nu} \text{ mode at mid-E;} 
  \end{cases}
  \]
- new fission $\bar{\nu}$ fluxes suggests that all SBL reactor experiments are observing a deficit;

however, these “hints” for sterile neutrinos are not in agreement among them:

- MiniBooNE asymmetry in $\nu/\bar{\nu}$ requires CP violation, hence at least two sterile $\nu$’s;
- (3+2) models reconcile APP data, but DIS ones still show strong tension;
- attempts to include the low-E excess in the game further increase such tension;
- new reactor fluxes reduce tension with DIS data only marginally;

efforts to produce an updated global analysis are presently under way [12];

⇒ we are still quite far from the solution of the LSND puzzle!

[12] J. Kopp, P. Machado, M. Maltoni, T.Schwetz, work in progress.