B-L and Neutrino Oscillations

Can We Fit LSND and MiniBooNE Simultaneously?

Jonathan Walsh
and
Ann Nelson

University of Washington
Seattle, WA

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Outline

An Apparent Conflict in Experiment

The recent null oscillation results of the MiniBooNE experiment seem to refute the positive oscillation results of LSND.

Significant differences between the two experiments:

- Baseline to energy (L/E) is the same, but MiniBooNE is at an order of magntiude higher energy
- The primary analyses for the experiments used anti-neutrinos (LSND) and neutrinos (MiniBooNE)
- The results are different – LSND found oscillations, MiniBooNE did not

A Possible Resolution

We introduce a model built on a $U(1)_{\text{B-L}}$ gauge interaction. Features of the model:

- An MSW-like potential that suppresses oscillations at high energy
- A 3+3 model, to include neutrino masses
- Can fit oscillations at LSND and MiniBooNE
- A low energy excess at MiniBooNE comes out of the model naturally
- High potential to see oscillations in anti-neutrinos at MiniBooNE

The LSND Experiment

- Searched for both $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ and $\nu_\mu \rightarrow \nu_e$ oscillations
- Baseline of 30 m from target to detector. The neutrino mass sensitivity in standard oscillation models is governed by $(L/E)^{-1}$:

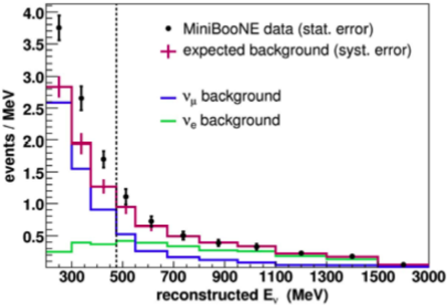
$$(L/E)^{-1} \sim 0.1 - 1.0\,\mathrm{eV}^2$$

The experiment found oscillations:

$$P(\bar{\nu}_\mu \rightarrow \bar{\nu}_e) = 0.264\% \pm 0.081\%$$
$$P(\nu_\mu \rightarrow \nu_e) = 0.26\% \pm 0.11\%$$

The MiniBooNE Experiment

- Searched for $\nu_\mu \rightarrow \nu_e$ oscillations, and was designed to refute or confirm the results of LSND
- Covered the $(L/E)^{-1}$ range of LSND, but with an energy range of 200 to 3000 MeV
- A speculative excess below 475 MeV was seen, but the source is unclear



The Effects of a $U(1)_{B-L}$ Gauge Interaction in the Neutrino Sector

- A new flavor universal potential in matter
  - MSW-like, dependent on the B-L charge density in matter
  - Can generate large potential, $V \gg V_{MSW}$
- A large potential suppresses oscillations at high energy
  - Can explain MiniBooNE
- Need B-L to be spontaneously broken
  - Dirac masses respect the symmetry
  - Majorana masses do not – can use the scalar ϕ that breaks the gauge symmetry to generate them
- Sterile neutrinos are needed
  - To give the neutrinos masses
  - To make the potential non-universal

Interactions in the Model

- Uses a spontaneously broken $U(1)_{B-L}$ gauge interaction with a light vector ($m_\gamma < m_e$) and weak coupling ($g \ll 1$)
- Expand the Hamiltonian to leading order in the neutrino masses

$$\mathcal{H} \approx E + \frac{1}{2E}\mathcal{M}^\dagger\mathcal{M} + \mathcal{V}$$

- Write $\mathcal{H}$ in the flavor basis
- Build the potential matrix $\mathcal{V}$ and mass matrix $\mathcal{M}$

The Potential Term

The strength of the potential is

$$V = \frac{g^2}{4m_\gamma^2}\rho_{\text{B-L}}$$

with sign (-) for active and (+) for sterile. The potential matrix $\mathcal{V}$ is, with I_3 the 3-dimensional identity,

$$\mathcal{V} = \begin{pmatrix} -V \cdot I_3 & 0 \\ 0 & V \cdot I_3 \end{pmatrix}$$

Electroweak constraints – we will be interested in the region:

- $V > 10^{-9}$ eV
- $m_\gamma < m_e$
- $\rho_{B-L} = 10^{28}$ charges/m^3

The strongest constraint comes from g-2 of the electron:

$$g \leq 9 \cdot 10^{-6} \Rightarrow m_\gamma < 1.8 \text{ keV}$$

Neutrino masses

Neutrino mass terms:

$$\begin{array}{rl} \text{Dirac} & m_{ij}\nu_i N_j + h.c. \\ \text{Majorana} & \lambda_{ij}\phi N_i N_j + h.c. \end{array}$$

If ϕ is doubly charged, the Majorana mass terms do not break the gauge symmetry and the Majorana masses are

$$M_{ij} = \lambda_{ij}\langle\phi\rangle$$

The sterile neutrino flavor basis is irrelevant – use a basis where the Majorana mass matrix $\mathcal{M}_s$ is diagonal:

$$\mathcal{M}_s = \begin{pmatrix} M_1 & 0 & 0 \\ 0 & M_2 & 0 \\ 0 & 0 & M_3 \end{pmatrix}$$

The neutrino mass matrix

The model is much simpler if the Dirac masses are degenerate – then in some basis, the Dirac mass matrix is proportional to the identity

$$\mathcal{M}_d' = m \cdot I_3$$

There are 3 real angles φ_i needed to rotate the flavor basis into this one – they are parameters of the model. In the same basis, the total mass matrix is simple:

$$\mathcal{M}' = \begin{pmatrix} 0 & m \cdot I_3 \\ m \cdot I_3 & \mathcal{M}_s \end{pmatrix}$$

and

$$\mathcal{M}'^{\dagger}\mathcal{M}' = \begin{pmatrix} m^2 \cdot I_3 & m\mathcal{M}_s \\ m\mathcal{M}_s & \mathcal{M}_s^2 \end{pmatrix}$$

which is 2-by-2 block diagonal.

The Hamiltonian and Mixing

The complete Hamiltonian for the system in the rotated flavor basis (where $\mathcal{M}_d$ is diagonal) is:

$$\mathcal{H}' = E + \frac{m^2}{2E} + \frac{1}{2E}\begin{pmatrix} -2VE & m\mathcal{M}_s \\ m\mathcal{M}_s & 2VE + \mathcal{M}_s^2 \end{pmatrix}$$

We have a mini-seesaw effect – one regulated by the size of V.
The last term in $\mathcal{H}'$ is diagonalized by the three mixing angles given by

$$\tan 2\theta_i = \frac{2mM_i}{4VE + M_i^2}$$

We analyze oscillations between two active flavors numerically. Since oscillations are suppressed when $\theta_i \to 0$, we study limits of the mixing angle to pick a favorable region of parameter space to fit LSND and MiniBooNE.

Oscillations Between Active Flavors

If the M_i are of the same order, then the following limits have $\theta_i \to 0$ and completely suppress oscillations:

$$VE \gg m^2, M_i^2 \qquad \text{— the MiniBooNE limit}$$
$$m^2 \ll VE, M_i^2 \qquad M_i^2 \ll VE, m^2$$

To see oscillations at LSND, these limits give a region for numerical analysis:

$$m^2 \lesssim M_i^2 \sim VE_{LSND}$$

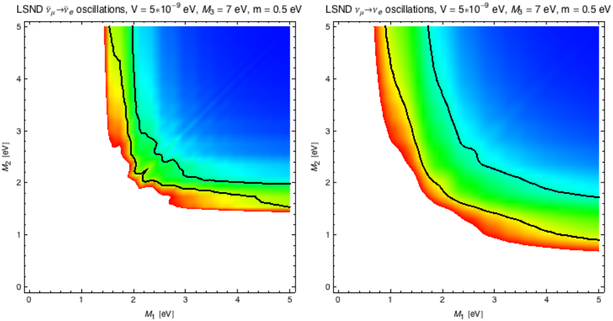
which ensures that at MiniBooNE, the high energy limit is in effect:

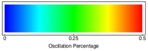
$$m^2 \sim M_i^2 \ll VE_{MB}$$

We pick values for the three angles ϕ_i, and take the value of m from the sensitivity range set by $(L/E)^{-1}$ for LSND and MiniBooNE.

Results for Oscillations at LSND

LSND oscillations for $\bar{\nu}$ (left) and ν (right)
Contours are at the limits set by LSND

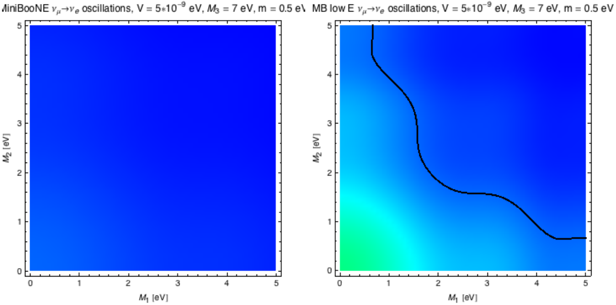




Oscillation Percentage

Results for MiniBooNE

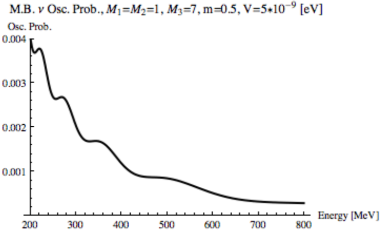
MiniBooNE oscillations above (left) and below (right) 475 MeV
Contours are at $P(\nu_\mu \to \nu_e) = 0.05\%$

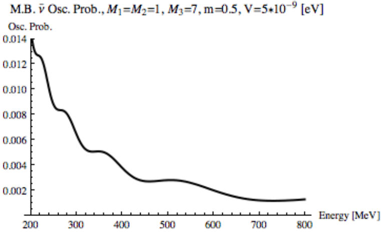


A low energy excess, like that seen at MiniBooNE, comes naturally in the model – need to fit to the oscillation probability corresponding to the excess.

More on MiniBooNE: Low Energy Excess

The low energy excess qualitatively fits -
for both ν (left) and $\bar{\nu}$ (right):

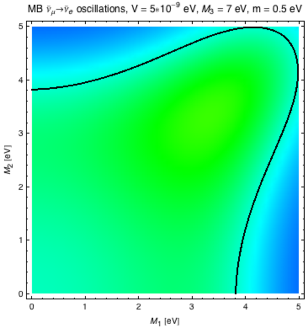




Therefore, we can fit to the excess seen at MiniBooNE
in $\nu_\mu \to \nu_e$ oscillations

MiniBooNE and $\bar{\nu}$ Oscillations

Even though MiniBooNE is at higher energy, the reversal in sign of V enhances oscillations. Therefore, MiniBooNE could see $\bar{\nu}_\mu \to \bar{\nu}_e$ oscillations:



A numerical study is needed to definitively say what the spectrum of predictions for MiniBooNE $\bar{\nu}$ oscillations is – but we expect to see oscillations there

Oscillations at Other Experiments

Many other oscillation experiments, especially atmospheric and differ from LSND and MiniBooNE in significant ways:

- In many experiments, neutrinos either do not propagate through matter or do so only over a limited baseline, mitigating the effect of the potential term
- The sensitivity range of the experiment, determined by $(L/E)^{-1}$, is not the same as LSND and MiniBooNE – thus much of the oscillations average out
- The current theory works very well to describe these experiments – our model must integrate with the current oscillation model to fit a larger range of experiments

Other experiments will have an impact on the model, most likely in determining the secondary parameters ϕ_i or the scales of the Majorana masses

Conclusions

- We have presented a model for neutrino oscillations that accommodates the results of LSND and MiniBooNE
- A potential provided by $U(1)_{B-L}$, much stronger than V_{MSW}, can give strong energy dependence for oscillations
- Lower energy experiments at the same $(L/E)^{-1}$ typically see more oscillations than higher energy experiments
- The low energy excess seen at MiniBooNE comes naturally in the model
- Anti-neutrinos and neutrinos behave very differently
- We expect MiniBooNE to see oscillations in $\bar{\nu}$
- See our forthcoming paper

Thanks to the organizers for this wide-ranging and informative conference

Extra Slides

The oscillation probability can be written concisely if we assume $\sin\phi_3 = 1$. Then the probability for oscillation between the first two active flavors, at fixed baseline and energy, is:

$$P_{1\to 2}(L,E) = 4\cos^2\phi_2 \sin^2\phi_2 \Big[\cos^2\phi_1 A_{13} + \sin^2\phi_1 A_{23} - \cos^2\phi_1 \sin^2\phi_1 A_{12} - \cos^4\phi_1 A_{11} - \sin^4\phi_1 A_{22} - A_{33} \Big]$$

$$\begin{aligned} A_{ij} &= \cos^2\theta_i \cos^2\theta_j \sin^2\left[\gamma\left(\frac{M_i}{m}\tan\theta_i - \frac{M_j}{m}\tan\theta_j\right)\right] \\ &+ \sin^2\theta_i \sin^2\theta_j \sin^2\left[\gamma\left(\frac{M_i}{m}\cot\theta_i - \frac{M_j}{m}\cot\theta_j\right)\right] \\ &+ \cos^2\theta_i \sin^2\theta_j \sin^2\left[\gamma\left(\frac{M_i}{m}\tan\theta_i + \frac{M_j}{m}\cot\theta_j\right)\right] \\ &+ \sin^2\theta_i \cos^2\theta_j \sin^2\left[\gamma\left(\frac{M_i}{m}\cot\theta_i + \frac{M_j}{m}\tan\theta_j\right)\right] \end{aligned}$$

$$\gamma = \frac{m^2 L}{E} \qquad \tan 2\theta_i = \frac{2mM_i}{4VE + M_i^2}$$