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MiniBooNE “Windows on the Universe”*

RAY STEFANSKI

Fermi National Accelerator Laboratory, PO Box 500, Batavia, IL 60510, USA
stefanski@fnal.gov

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We discuss the current state of measurements taken by MiniBooNE, and emphasize the uniqueness of neutrino oscillations as an important probe into the “Windows on the Universe.”

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1. Introductory Remarks

Progess in the last few decades has left neutrino physics with several vexing issues. Among them are the following questions: [1]

- Why are lepton mixing angles so different from those in the quark sector?
- What is the most probable range of the reactor mixing angle?
- Is the atmospheric mixing angle maximal?
- What is the number of fermion generations?

These are some of the issues that neutrino science hopes to study; this article will explore these questions as part of a more general scientific landscape, and will discuss the part MiniBooNE might play in this exploration.

2. Solar, atmospheric, reactor, and accelerator measurements

Measurements of the solar neutrino flux, the atmospheric neutrino flux, and related reactor and accelerator measurements have established that neutrinos are massive. In a three-neutrino-family picture, mixing can be described as the product of three mixing matrices. Leaving out two Majorana phases that are not observable in os-

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cillation processes;

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{i\delta_{CP}} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta_{CP}} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s12 & 0 \\ -s12 & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix} \quad (1)$$

where $c_{ij} = \cos\theta_{ij}$, and $s_{ij} = \sin\theta_{ij}$. The three mixing angles are [2]

$$\begin{array}{ll} \sin^2(2\theta_{12}) = 0.87 \pm 0.03 & solar \\ \sin^2(2\theta_{23}) > 0.92 & atmospheric \\ \sin^2(2\theta_{13}) < 0.15, CL = 90\% & reactor \end{array} \quad (2)$$

The mass squared differences are shown in equations (3). [2] (The sign of Δm^2_{32} is not known, and therefore, the mass hierarchy is unknown.)

$$\begin{array}{ll} \Delta^2_{21} & = (7.59 \pm 0.20) \times 10^{-5}\ eV^2 \\ |\Delta^2_{32}| & = (2.43 \pm 0.13) \times 10^{-3}\ eV^2 \end{array} \quad (3)$$

The combined result of four LEP experiments limits the number of light neutrino families: [3]

$$N_\nu = 2.984 \pm 0.008. \quad (4)$$

The cosmological constraint on the sum of active neutrino masses is [4]

$$\begin{array}{l} \Sigma m_\nu \leq 0.28\ eV\ \ (95\% CL), \\ \Sigma m_\nu \leq 0.47\ eV, \end{array} \quad (5)$$

where the second limit in equations (5) is the result of relaxing some assumptions in the analysis. (For a more comprehensive review of neutrino oscillation measurements, present and future, see Thomas and Vahle.) [5]

3. Tri-bimaximal mixing

Within the constraints posed by equations (2), θ_{13} might be equal to zero. Then equation (1) collapses to the product of two matrices, and the dependence on the CP phase can be removed. Because θ_{13} literally defines the character of neutrino mixing and is connected to the possibility of CP violation (CPV) in the neutrino sector— perhaps similar to CPV found in the quark sector— measurements of $\sin^2(2\theta_{13})$ are either taking place or in preparation in several reactor and accelerator experiments, [6] with the expectation of reducing the limit on this parameter by roughly an order of magnitude by mid-decade. [7]

We can, for the moment, assume that making $\theta_{13} = 0$ may be a good approximation, and that $\theta_{23} = \pi/4$ and $\theta_{12} \simeq 35.3\,$deg, such that $\sin^2(\theta_{12}) = 1/3$ – that is, that the mixing angles take values closely resembling the measured values. These asssumptions form the basis of what phenomenologists refer to as the tri-bimaximal mixing model, or the Harrison-Perkins-Scott pattern. [8]

If θ_{13} is zero, it may reflect a symmetry in nature. Altarelli and Feruglio [9] proposed a model based on permutation group A4, "which is the group of even permutaions of four objects, isomorphic to the group of discrete rotations in the three-dimensional space that leave invariant a regular tetrahedron." [1] The association of this symmetry with the geometry of the regular tetrahedron may be motivated by the fact that the angle between two faces of the object is $\sin^2(\theta) = 1/3$. This is an example of the way that models can be constructed in which the mass matrices are invariant under certain group elements, which in turn are connected to the symmetry of a geometrical object the group describes. [10]

The discovery of a possible A4 symmetry, or a variation of it, in the description of neutrino mixing may lead to finding a relationship between the quark and lepton sectors, and a better understanding of the physics behind the differences between the quark and lepton mixing matrices.

4. Theoretical framework

Within a broader picture, a suggested step beyond the "Standard Model of Particle Physics" would include the quark and lepton sectors in the same symmetry, perhaps as part of a Grand Unified Theory (GUT). The minimal supersymmetric $SU(5)$ model [11] is built upon the picture of three families of quark and lepton pairs described by $SU(3)$ symmetries among three quarks with interactions mediated by gluons, and the electro-weak $SU(2) \otimes U(1)$ symmetries of leptons whose interactions are mediated by a photon and three vector bosons, and includes the Higgs mechanism. The model replaces B and L conservation with R-parity conservation, where R-parity is defined as B-L. Interactions among the members of the group, including the quarks and leptons, are mediated by massive bosons.

This model, however, predicts a larger cross-section for proton decay than exists in nature, and therefore, requires extensions such as $SO(10)$ to adequately represent the physical world. Newer, more representative models of nature should also attempt to find an explanation for Dark Matter and Dark Energy in the universe. The possibility that extensions of these models might involve the existence of extra dimensions or new fundamental particles is open to speculation. For example, sterile neutrinos [presumably right-handed neutrinos that cannot participate in the V−A electroweak interactions and are therefore not detectable, that is, they do not violate equation (4)] might be a part of an extended description of nature.

The results published by MiniBooNE and discussed below provide some hints at possible avenues of approach.

5. MiniBooNE

MiniBooNE [12] operates in the Booster Neutrino Beam at Fermilab, a beam of mainly muon neutrinos created by the decay of mesons produced by 8-GeV protons interacting in a beryllium target, and focussed by a magnetic horn. The decay volume is 50 m in length, and the MiniBooNE detector is located 541 m from the target.

It is an 800-ton spherical detector, 12 m in diameter, filled with mineral oil. Light generated within the detector by Cherenkov radiation, or by scintillation caused by ionizing particles, is observed by photo-multiplier tubes. Measurements are taken on appearance events of ν_e ($\bar{\nu}_e$) in a ν_μ ($\bar{\nu}_\mu$) beam and disappearance events of ν_μ ($\bar{\nu}_\mu$) from a ν_μ ($\bar{\nu}_\mu$) beam. The survival probabilities, under the reasonably accurate simplifying assumption of two-neutrino-flavor mixing, is given by

$$\begin{aligned} P_{\nu_\mu \to \nu_e} &= \sin^2(2\theta)\sin^2(1.27\tfrac{\Delta m^2 L}{E}), \\ P_{\nu_\mu \to \nu_x} &= 1 - \sin^2(2\theta)\sin^2(1.27\tfrac{\Delta m^2 L}{E}), \end{aligned} \tag{6}$$

where Δm^2 is the relevant neutrino mass squared difference and θ is the effective mixing angle for $\nu_\mu \to \nu_e$.

Charged current quasi-elastic (ccqe) interactions are the primary signal in oscillation measurements in MiniBooNE. Loosely speaking, the ccqe interactions of ν_μ, $\bar{\nu}_\mu$, ν_e, and $\bar{\nu}_e$ are those that result in a corresponding charged lepton in the final state. The neutrino flux [13] and interaction rates are constrained by a very clean sample of ν_μ ccqe events in the detector – muons are unambiguously identified by range in the mineral oil and the appearance of the decay electron at the end of the muon track. The measurement strategy involves the identification of events with electromagnetic final states, that is, events that contain electrons or positrons, as would be expected in ccqe ν_e ($\bar{\nu}_e$) interactions. Background estimates are made using the constrained neutrino flux and an event simulation model, NUANCE. [14] The expected photon backgrounds are determined from π^0 decays, the simulation of photo-nuclear effects, and estimates of photons generated in the material surrounding the detector.

5.0.1. ν_e *and* $\bar{\nu}_e$ *appearance*

The results of appearance searches are given in Table 1 for both ν_e [15] and $\bar{\nu}_e$. [16] The data are divided into bins of E_ν^{QE}. The error contains both statistical and systematic effects, and σ is calculated as $(data - background)/error$. L/E is a rough estimate of this oscillation parameter calculated as the mean distance from the neutrino source, $\sim$ 520m, divided by the mean of the neutrino energy range.

Table 1. Results of MiniBooNE Appearance Searches

neutrino type	energy range E_ν^{QE} (MeV)		total number of events	backgd	data minus backgd	error	σ	L/E L$\sim$ 520m
ν_e	200	475	544	415.2	128.8	43.4	3.0	1.3
	475	1250	408	385.9	22.1	35.7	0.6	0.6
$\bar{\nu}_e$	200	475	119	100.5	18.5	14.3	1.3	1.54
	475	675	64	38.3	25.7	7.2	3.6	0.9
	675	3000	94	95.	-1.	16.5	-0.1	0.28

The 475 to 3,000 MeV range for the $\bar{\nu}_e$ numbers in Table 1 were taken from the published results, and broken into two bins, assuming uncorrelated errors, which should be approximately correct.

The results in Table 1 can be divided into low-energy (LE) and high-energy (HE) parts. LE includes bins with $E_{\nu}^{QE} < 475MeV$, and HE includes bins with $E_{\nu}^{QE} > 475MeV$

The LE result shows a three σ excess in ν_e between 200 and 475 MeV, but no significant excess $\bar{\nu}_e$–It should reflect itself as a $\sim$ 30-event excess in $\bar{\nu}_e$ appearance compared to 18.5 seen in the data. This observation is known as the MiniBooNE low-energy anomaly. According to the authors, "The events are consistent with being either electron events produced by CC scattering ($\nu_e \rightarrow e^- X$) or ($\bar{\nu}_e \rightarrow e^+ X$) or photon events produced by NC scattering ($\nu C \rightarrow \nu \gamma X$)."

The HE result shows no oscillation behavior in ν_e but a significant oscillation in $\bar{\nu}_e$, [17] where if the fit to equations (6) is taken from 475 to 3000 MeV it yields a 0.5% probability for a background-only hypothesis. As we'll see, the HE $\bar{\nu}_e$ result is significant when combined with the LSND[18] $\bar{\nu}_e$ appearance measurement.

5.0.2. *ν_μ and $\bar{\nu}_\mu$ Disappearance*

Searches published in 1984 for ν_μ and $\bar{\nu}_\mu$ disappearance at Fermilab, [19] and for ν_μ disappearance in a separate experiment at CERN, [20] set limits on the existence of the transition $\nu_\mu \rightarrow \nu_x$. The ν_μ lower limit was about $\Delta m^2 < 0.26eV^2$, and the $\bar{\nu}_\mu$ lower limit was about $\Delta m^2 < 30.0eV^2$. If the LE excess were due to oscillation phenomena, a signal might also be seen in the ν_μ disappearance data. MiniBooNE has not seen a signal in the ν_μ [21] disappearance data, and reestablishes limits roughly comparable to the 1984 results mentioned above. The MiniBooNE $\bar{\nu}_\mu$ appearance result [22] suggests that a mass squared difference at about 0.1 eV^2 might exist, and presumably be seen in the $\bar{\nu}_\mu$ disappearance data. MiniBooNE has not seen a signal in $\bar{\nu}_\mu$ disappearance data, extending the $\bar{\nu}_\mu$ limits to lower Δm^2 of ~ 1 eV^2. However, $\bar{\nu}_\mu$ data are still being taken by MiniBooNE, and a combined analysis is being carried out with the SciBooNE collaboration,[23] which may result in a confirming signal in the $\bar{\nu}_\mu$ appearance result.

5.1. *LSND and $\bar{\nu}_e$ appearance*

The Liquid Scintillator Neutrino Detector (LSND) [18] experiment ran at the Los Alamos National Laboratory in the 1990s. The beam was generated by the decay of stopped muons in a copper target, and the detector was located 30 meters from the target. The mean beam energy was about 30 MeV, so the oscillation parameter (L/E) for this experiment was $\sim$ 1. The decay kinematics of pions and muons-at-rest are well known, so that the flux of $\bar{\nu}_\mu$ used to search for the transition $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ was constrained, as was the $\bar{\nu}_e$ background from μ^- decays. The experiment involved doing a search for $\bar{\nu}_e$ appearance in the $\bar{\nu}_\mu$ beam by detecting the reaction $\bar{\nu}_e p \rightarrow e^+ n$. The e^+ is detected as it annihilates in the scintillator and the 2.2-MeV

γ from the reaction $np \rightarrow d\gamma$ creates a delayed electromagnetic shower visible in the detector.

LSND published a 3.8 σ observation of $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$; MiniBooNE was constructed at Fermilab to test this result.

The LSND result consists of the detection of events that satisfy the $\bar{\nu}_e$ signature, compared to background events taken with the beam off. The excess of 117.9 $\pm$ 22.4 was then corrected for intrinsic $\bar{\nu}_e$ created at the beam stop, 19.5 $\pm$ 3.9, and misidentification of ν_μ and $\bar{\nu}_\mu$, 10.5 $\pm$ 4.6, giving the result

$$Data - Background = 87.9 \pm 22.4(stat) \pm 6(syst).$$

Recently, Zhemchugov [24] reported on new particle production data from the HARP measurement [25] that suggest a correction to the intrinsic beam background to 32.5 $\pm$ 9.3, which results in a decrease in significance of the LSND result to 3 σ. The LSND result, with the Zhemchugov update, is

$$Data - Background = 74.9 \pm 22.4(stat) \pm 10.3(syst).$$

6. MiniBooNE and LSND combined

Taken together, MiniBooNE and LSND offer a serious hint that something may be going on in the antineutrino sector, beyond the physics of the simple three-neutrino-family model. As can be seen from Table 1, the signal seen in the MiniBooNE HE $\bar{\nu}_e$ appearance data occurs at nearly the same $L/E \sim 1$ as in the LSND $\bar{\nu}_e$ appearance measurement–all the more intriguing in the absence of an oscillation signal in the MiniBooNE HE ν_e appearance data. MiniBooNE may be able to confirm the HE $\bar{\nu}_\mu$ signal if it is seen in $\bar{\nu}_\mu$ disappearance measurements.

Additionally, MiniBooNE sees a LE excess in ν_e appearance data, at $L/E \sim 1.4$. These measuements together constitute an interesting set of possibilities that will require further study.

7. Phenomenology

Some of the phenomenology inspired by the MiniBooNE/LSND results are discussed in this section.

If we neglect the low-energy excess, for no justifiable reason except to study the possibility, then in the absence of an oscillation signal in the neutrino sector a three-neutrino picture can be maintained. The neutrino and antineutrino masses would not be the same, which implies a breakdown in CPT conservation and Lorentz invariance. We could, for example, have the two lowest masses be the same in neutrinos and antineutrinos, but invoke a significant difference between the third set of masses, with the $\bar{\nu}$ mass squared difference at roughly 0.1 eV^2. Choudhury, Datta, and Kundu [26] studied the compatibility of various experimental results and found many iterations of mass and mixing angle that preserve the three-neutrino picture.

The low-energy excess can be addressed within the constraints of the Standard Model by the use of anomaly-mediated neutrino-photon interactions.[27] This is a proposed new process that couples the photon, Z-boson and the ω-meson, and will induce neutrino-photon interactions at finite baryon density by coupling the Z-boson to neutrinos, thereby creating a single photon background that could explain the low-energy excess.

If we accept the possibility of a breakdown in CPT conservation and Lorentz invariance, then neutrino-antineutrino oscillations are possible, perhaps even inevitable. There are several papers that propose an explanation of the MiniBooNE low-energy anomaly and the LSND effect by mixing of light neutrinos and antineutrinos only, and contain $\nu_e \rightleftharpoons \nu_\mu$ and $\bar{\nu}_e \rightleftharpoons \bar{\nu}_\mu$ resonant features. [28]

The breakdown in Lorentz invariance is incorporated in a three-global-parameter model[29] that makes specific predictions for oscillation behavior in several experiments, including MiniBooNE. The model can be fit for both appearance and disappearance experiments.

There are also models proposed that allow for the existence of sterile neutrinos, which in a world of extra dimensions can travel between branes, whereas the active neutrinos are confined to the brane; this proposal leads to modification in "dispersion relations" between sterile and active neutrinos and provides a means of fitting disparate results between MiniBooNE and LSND. [30] One such model predicts oscillations in the MiniBooNE HE $\bar{\nu}_\mu$ signal.

Several authors over time have considered the other side of the V-A symmetry, that is, the possible existence of a parallel world in which the standard electroweak interaction obeys a V+A symmetry.[31] Neutrinos in this parallel world would be sterile, obeying the LEP limits on active neutrino families in equation (4), but could conceivably mix with active neutrinos.

There has also been work on developing a 4-neutrino model, three active and one sterile, to fit a wide range of recent experimental results. [32] Models have also been studied with more than one sterile neutrino. [33]

Nelson and Walsh [34] introduced a model of three-sterile-neutrino families paired with the conventional three-active-neutrino families, and subject to a gauged B-L interaction – leading to an explanation of current MiniBooNE measurements and a prediction for the $\bar{\nu}_e$ appearance measurement now in progress. The prediction was made before the apparent oscillation signal was seen.

8. Concluding Remarks

Neutrino oscillations offer a powerful tool for exploring the unknown universe. The successes of the past, including the discovery of neutrino mass and the measurement of the mixing matrices and mass squared differences, have focused our attention on the world of three standard neutrinos and the search for the value of θ_{13} and a possible violation of CP conservation in the neutrino sector. But this field of study may have much more to offer: It's about not only measuring the elements of the mixing matrices or confirming the MiniBooNE/LSND result, but also searching for an improved understanding of the physical unknowns in our universe. It's imperative that experiments with greater neutrino flux, different neutrino flavors, a wide range of neutrino energies and more sensitive detectors explore the largest range of mixing parameters possible. In this way, neutrino oscillations may be a means of further opening "Windows on the Universe."

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