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Nus and Anti-nus from MiniBooNE: Searching for the Shadow of the Ghost

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Abstract.
The latest results from MiniBooNE, the short baseline neutrino experiment operating on the 8 GeV booster's neutrino beam line (the BNB) at Fermilab, are discussed. The standard three active generation model of neutrino oscillations is now grounded firmly by experimental data. Studying the properties of neutrinos at the few percent level and below may uncover new properties of neutrinos and their oscillations and provide a path to physics beyond the standard neutrino model.

1. Introduction and Motivation

The neutrino was discovered over 50 years ago (Reines and Cowan 1953) and is still the least understood of all of the quarks and leptons. The nature of the quantum field describing them is still undetermined. Because neutrinos have no electric charge to conserve, they might be described by several fields including Majorana, Weyl, or Dirac spinors.

The right handed chiral parts of the quarks and charged leptons do not interact weakly, i.e. they are $SU(2)_L$ gauge singlets, and have identically the same mass as their left handed counterparts. Analogously, the right handed neutrino components would be without interactions, save gravitation, and would make them nearly impossible to observe. Furthermore, their masses of the right handed states are not constrained to be the same as their left handed components.

The right handed neutrino components would thus be "sterile" if the followed suit with the corresponding charged lepton components. They would not, however, be expected to have unknown the same masses as there right handed counterparts. There is no direct experimental evidence for the existence of sterile neutrinos, and the search for them has been on-going for decades. While neutrinos have been dubbed the "ghost particle" a fitting moniker for sterile neutrinos might be "the shadow of the ghost".

If the right handed components are without any interactions other than gravity, they would not be necessarily constrained to the 4 dimensional surface determined by the standard $SU(2)_L \times U(1) \times SU(3)_{color}$ in higher dimensional theories of intereractions. Those theories allow the sterile neutrino to, for example, take shortcuts in higher dimensional spaces (Hollenberg et. al. 2009; Hollenberg and Pas 2009), and cause complex and interesting resonant oscillation phenomena.

1.1. Cosmology and Astrophysics

The existence of sterile neutrinos would have a large impact on cosmology and astrophysics. In astrophysics, neutrinos play an important role in core collapse supernova (Type II SN), where more than 99% of the energy radiated by the collapse is in the form of neutrinos. Indeed, neutrinos were observed coming from the nearby supernove 1987a by the IMB and Kamiokande experiments. Type II SN explosions are thought to be the best potential candidate site for the r-process to occur, thereby producing all of the naturally occuring elements heavier than iron, such as uranium. The current models of Type II SN preclude this possibility. The intense flux of neutrinos emmitted by the supernova break up the deuterium via their neutral current interactions with it thereby suppressing the r-process at its first stage.

Medium weight sterile neutrinos of around a GeV are thought to be a candidate for pruducing the correct baryon asymmetry of the universe. Through the effects of CP violating neutrino oscillations those sterile neutrinos could achieve the three conditions put forth by Sakharov: non-equilibrium, CP violation, and B+L violation.

The leading candidate for dark matter is the sterile neutrino. The latest simulations of galaxy formation with cold dark matter produce too many clusters of dark matter which would seed dwarf galaxies at a level not observed locally. A lighter form of dark matter, for example a 1-5 keV mass sterile neutrino, might solve this difficulty.

While certain cosmological models disfavor too many light neutrinos, the purpose of this paper is not to discuss what is allowed or not allowed by cosmological models, but rather interpret data recorded by experiments on neutrinos themselves. It might be that the effects of sterile neutrinos are not directly observable by experiment, in which case they will forever remain speculative possibilites, however we are far from being in that situation at the present time.

1.2. Looking for Shadows

The potential observable effects of sterile neutrinos are manifold given that little is known about them. While they would not participate directly in the weak interaction, they could possess weaker interactions medeated by right handed bosons and more complicated Higgs sector interactions. Light steriles are expected to mix with the three active neutrinos at some level, in a way similar to active-active neutrinos mixing. The 3-by-3 unitary matrix would be enlarged to a 6-by-6 unitary matrix in the case of three additional sterile states. That would allow a number of new Δm^2 and mixing angle parameters to enter an arena with limited information in the way of experimental constraints.

A heavier sterile neutrino could potentially decay. For example, dark matter sterile neutrinos of order 1 keV might decay into a single photon plus a lighter active neutrino(Petraki and Kusenko 2007). This would produce a monoenergetic photon signal observable by xray detectors aboard satellites(1). Higher mass sterile neutrinos might be produced in neutral curent neutrino interactions and decay inside large neutrino detectors. While there are many limits on such possibilies they have certainly not been ruled out and are worth searching for.

Sterile neutrino decays have been proposed to explain the LSND events excess (PalomaresRuiz et. al. 2005; Schwetz 2008). A sterile neutrino in the 1

GeV mass range might be produced via neutral current reactions. Its subsequent decay could produce small detectable signals neutrino interactions(Gninenko 2009). Under some assumtions, this sort decay can leave a signature of low energy photons in detectors like MiniBooNE, nearly indistiguishable from electron neutrino events.

1.3. Neutrino Oscillations and the νMSM

Over the past decade reliable measurements of neutrino oscillation parameters have solidified the larger features of active-active neutrino oscillations. The neutrino data provided by SNO (Ahmad 2002) and the Kamland (Abe 2008) data leave little doubt that large amplitude, $\bar{\nu}_e$ disappearance with $\Delta m^2 \sim few \times 10^{-5}\ eV^2$. Similarly, the SuperK (Fukuda 2001), K2K (Ahn 2006), and most recently the beautiful data from the MINOS detectors (Adamson 2007) show nearly maximal disappearance in ν_μ.

We shall call this standard picture the minimal standard model of neutrinos, or νMSM. The νMSM does not contain the gauge singlet right handed component of the neutrinos, which is a reasonable position to take since there is no direct experimental evidence for their existance. There are theoretical reasons to believe that the right handed neutrino components exist, but have been made heavy through a "see-saw" mechanism.

2. Hints for Physics Beyond the νMSM in Neutrino Oscillation Experiments

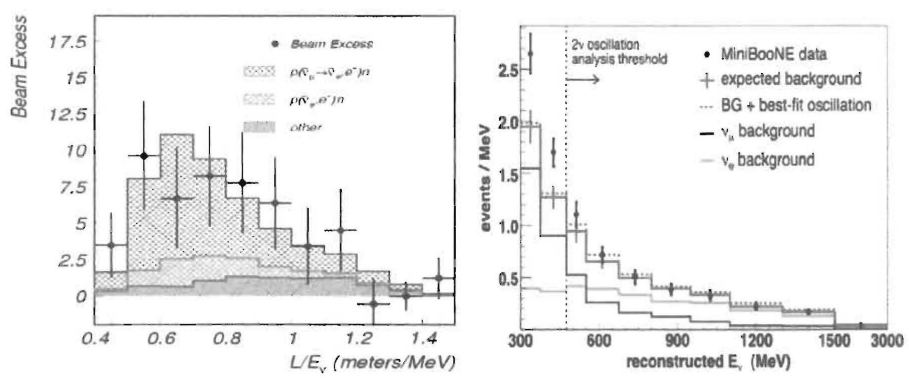

Figure 1. Two experimental results results show unexpected excess events: in the first panel, LSND in $\bar{\nu}_\mu \to \bar{\nu}_e$ and in the second panel, MiniBooNE in $\nu_\mu \to \nu_e$.

There are several indications for physics beyond the νMSM. The LSND experiment observed (Aguilar et. al. 2001) excess events in a stopped muon beam. This excess, reported at the 3.8σ significance, is shown in the first panel of Figure 1. The MiniBooNE experiment (Aguilar-Arevalo et. al. 2007) observed and unexplained excess of events in their low energy region 300 MeV to 475 MeV, as shown in the second panel of Figure 1.

In this article we discuss an update to the earlier MiniBooNE result in neutrino mode and also discuss the preliminary anti-neutrino data from MiniBooNE.

3. The Latest MiniBooNE Results

Since the first MiniBooNE neutrino oscillation paper (Aguilar-Arevalo et. al. 2007), the MiniBooNE collaboration has reviewed that analysis with an eye toward understanding the low energy electron-like data, i.e. neutrino energies of 300 MeV to 475 MeV. We have also analyzed much of the anti-neutrino mode data. A new analysis has emerged which give us much more confidence in the low energy region. In addition, a significant fraction of the anti-neutrino mode data ($3.39 \times 10^{20} pot$) has been analysed.

3.1. MiniBooNE Neutrino Mode Update

The first MiniBooNE oscillation analysis (Aguilar-Arevalo et. al. 2007) used only data with reconstructed neutrino energies above 475 MeV. We have now extended this analysis down to 300 MeV (Aguilar et. al. 2008). There were a number of improvements and oversights that were corrected. There were several improvements to the analysis, aside from correcting some minor bugs. The two major improvements were: the inclusion of nuclear photo-absorption in the detector simulation, and the rejection of single photon backgrounds at the periphery of the tank.

Nuclear Photo-Absorption It was brought to light that the GEANT3 code used to simulate the detector response leaves out a normally unimportant process, the absorption of photons by nuclei. As it turns out, this is a relevant process for the MiniBooNE analysis. One of our dominant background events in the electron-like sample are misidentified neutral current π^0 events where one of the resulting photons from the π^0 decay is not reconstructed. When such a photon is absorbed by a nucleus, the event lookes highly electron-like, and is usually mistaken for an electron. The inclusion of this process in our simulation has lead to a slight increase in our background predictions in the low energy region.

Rejection of Peripheral π^0 Events We have also uncovered a way to reject two large background in the low energy sample, similar to a strategy used by the LSND decay-in-flight analysis (Athanassopoulos et. al. 1997). Those backgounds, which are also single photon in nature, are mostly present near the wall of the MiniBooNE tank. Those backgrounds are both due to π^0s where one of the decay photons is missed.

In one case the π^0 is outside the fiducial volume and one of the photons sneaks through the veto barrier undetected leaving a single photon entering the tank. In the other case, the π^0 is produced inside the fiducial volume of the tank and one of the decay photons escapes the tank undetected.

The event selection was augmented to reject events in a triangular region of the visible energy vs. flightpath from the tank wall. Events at low energy and who would not have traveled far into the tank were eliminated by this cut, dramatically reducing the backgrounds mentioned above.

3.2. MiniBooNE Anti-Neutrino Mode

The anti-neutrino mode electron-like data (Aguilar-Arevalo et. al. 2009) was selected in an identical fashion as the neutrino data. The resulting backgrounds are very similar in nature to the neutrino mode backgrounds so that systematic errors associated with the event selection will tend to cancel.

There is an additional complication in the antineutrino analysis. Although the MiniBooNE horn polarity was switched to focus negatively charged particles, and hence yield predominantly anti-neutrinos, there are still a significant number of events produced by neutrinos. Nearly 30% of the events in anti-neutrino mode are due to neutrino interactions.

3.3. New Results

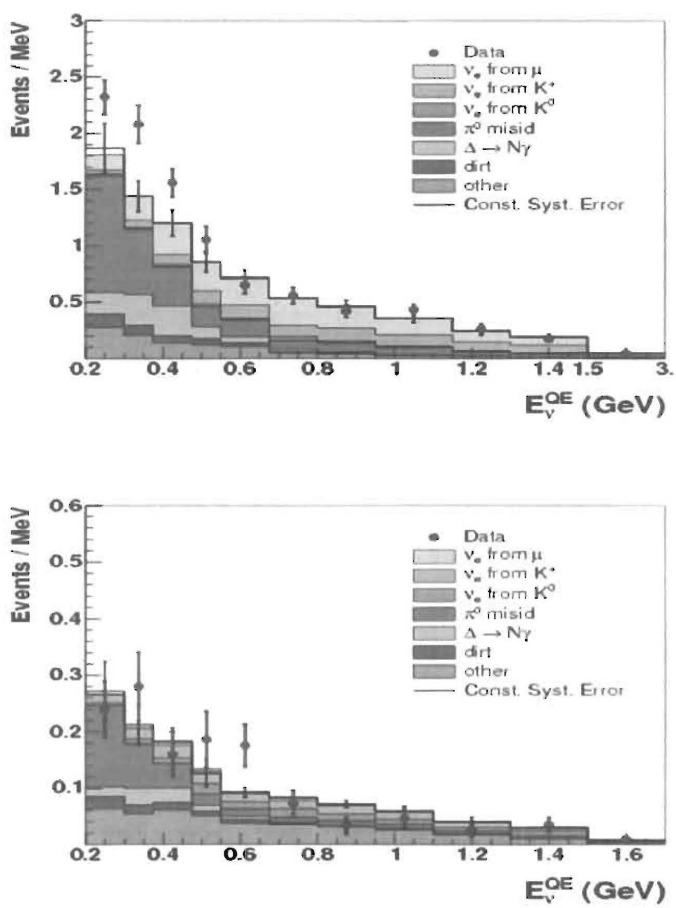

Figure 2. The latest electron-like event yields from MiniBooNE: in the first panel, neutrino mode, and in the second panel, anti-neutrino mode.

Figure 2 show the yields of electron-like events for neutrino mode (first panel) and anti-neutrino mode (second panel) along with their respective νMSM background predictions. A clear $128.8 \pm 20.4(stat) \pm 38.3(sys)$ excess of events is observed in the neutrino mode analysis. Without systematic errors, the neutrino mode excess has a significance of over 6σ, however large systematic errors reduce this to a 3σ significance.

The anti-neutrino electron-like event yields the the second panel of Figure 2 provide a first glimpse at anti-neutrino appearance in this energy range. The statistics are clearly much inferior to the neutrino mode data. It should be noted that the MiniBooNE anti-neutrino data are over shadowed by the much more sensitive LSND (Aguilar et. al. 2001) measurements of anti-neutrino appearance, however they still provide insight into the nature of the MiniBooNE neutrino mode excess.

While the statistcal power of the present anti-neutrino mode data is low, it apparently lacks the low energy excess seen in neutrino mode. In order to compare the two, a model for the excess must be assumed.

A postulated additional background, the "axial anomaly" (2) should have produced a significant excess in the anti-neutrino mode data. If it were the only additional source, MiniBooNE should have observed 40 additional low energy events, which are not seen. While the statistcal power of the data is too low in the present sample, we expect a clear picture to emerge as more anti-neutrino mode data is recorded and analyzed.

Another aspect of the data at this stage is that the lack of an excess in anti-neutrino mode is consistent with the neutrino mode excess under the assumption that it comes from neutrinos only. Therefore, oscillation phenomena that do not preserve CP invariance, or CPT invariance, could still explain the excess.

4. Interpretation

The LSND and MiniBooNE observations, while significant, by no means imply an oscillation phenomena is at work because both experiments were single detector experiments. In order to prove that an an oscillation phenomena underlies and excess of events, a second detector is needed to demonstrate the effect as a function of distance.

LSND, which ran at 30 meters from the LAMPF stopped muon source, had a surrogate near detector, the KARMEN experiment (3) at 17 meters distance from the ISIS stopped muon source. Ideally a second detector would run simultaneously in the same beam, however the null KARMEN result suggests that the LSND result is an oscillation phenomena.

The SciBooNE experiment ran at roughly 100 meters from the Booster Neutrino Beam (BNB) and will provide some insight into the MiniBooNE beam, however, there are several problems with the comparison. The SciBooNE detector is substantially different in design, and their efficiencies and backgrounds for electron-like events are not similar at all.

For muon neutrino events the SciBooNE-MiniBooNE comparison is more favorable. The only issue there is that the plastic scintillator used in SciBooNE as the neutrino target has a chemical stoiciometry of CH, whereas the mineral

oil neutrino target in MiniBooNE is CH_2. The extra hydrogen in mineral oil changes the cross section substantially, especially in anti-neutrino mode.

4.1. Comparing LSND and MiniBooNE

Figure 3 shows the LSND and MiniBooNE data, converted to oscillation probability, after they have been transformed into the variable L/E. A striking feature in the data is that the L/E regions of significant excess events do not overlap. Two solutions for a CP violating $3+2$ model are plotted on top of each. The first a "high-low" solution with $\Delta m_a^2 = 7.5eV^2$ and $\Delta m_a^2 = 0.25eV^2$ and the second a solution with $\Delta m_a^2 = 0.5eV^2$ and $\Delta m_a^2 = 0.25eV^2$. The $3+2$ model has enough freedom to accomodate the data

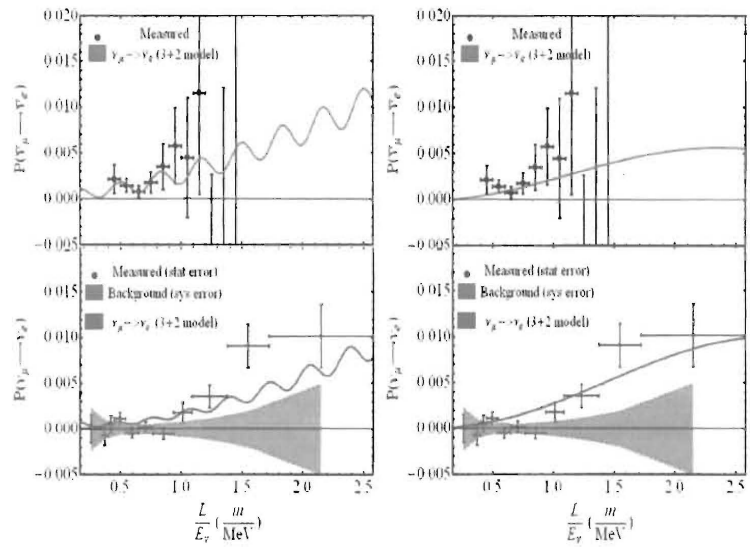

Figure 3. The LSND and MiniBooNE oscillation probabilities, transformed into the variable L/E : in the top panels, LSND and in the bottm panels, MiniBooNE. Two solutions for a $3+2$ model are plotted on top of each. The left panels show a "high-low" solution with Δm_a^2 $7.5eV^2$ and Δm_a^2 $0.25eV^2$ and the right panels show a solution with Δm_a^2 $7.5eV^2$ and Δm_a^2 $0.25eV^2$. The green band on the MiniBooNE panel represents the systematic error while the error on the points is statistical only.

5. Conclusions

The MiniBooNE experiment has been recording data since 2002. We have now run significant numbers of protons on target in both neutrino mode (positive focus) and anti-neutrino mode (negative focus). The comparison of the two data sets sheds light on the nature of the MiniBooNE low energy excess. A clear $128.8 \pm 20.4(stat) \pm 38.3(sys)$ excess of events is observed in the neutrino mode analysis. Without systematic errors, the neutrino mode excess has a significance of over 6σ, however large systematic errors reduce this to a 3σ significance.

The anti-neutrino mode data does not show an excess of events but is of lower statistical precision. By comparing it to the neutrino mode data we find that certain backgrounds like the axial anomaly (4) are disfavored. Since MiniBooNE cannot rule out the possibility of a unanticipated single photon background we feel that the resolution of this excess is an experimental question.

Without a near detector, the MiniBooNE analysis is hampered by large systematic uncertainties. However, if a MiniBooNE-like detector (or MiniBooNE itself) were run in a near position, the comparison between the near an far data would reduce systematic errors considerably. In the event that the low energy excess is due to an oscillation-like phenomena, the excess would mostly disappear. This would be a clear indication of physics beyond the standard neutrino model.

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