OscSNS: A Definitive Search for Sterile Neutrinos

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The SNS has a golden opportunity to pursue a precision neutrino physics program in a cost-effective manner, as an intense flux of neutrinos from stopped pion and muon decay are produced during normal SNS operations. The existence of light sterile neutrinos would be a major extension of the Standard Model, and sterile neutrino properties would be central to dark matter, cosmology, astrophysics, and future neutrino research. The OscSNS experiment will be able to prove whether active-sterile neutrino oscillations can explain the existing short-baseline anomalies.

I. EXECUTIVE SUMMARY

There exists an urgent need to address and resolve the growing evidence for short-baseline neutrino oscillations and the possible existence of sterile neutrinos. Such non-standard particles would have a mass above the mass scale associated with active neutrinos and were first invoked to explain the LSND anti-electron-neutrino appearance signal [1]. More recently, the MiniBooNE experiment has reported a 2.8 sigma excess of events in antineutrino mode [2] that is consistent with neutrino oscillations and with the LSND antineutrino appearance signal. MiniBooNE also observes a 3.4 sigma excess of events in the neutrino mode data [2]. Lower than expected neutrino-induced event rates using calibrated radioactive sources [3] and nuclear reactors [4] can also be explained by the existence of sterile neutrinos. Fits to the world's neutrino and antineutrino data are consistent with sterile neutrinos at a ~ 1 eV mass scale [5], although there is some tension between measurements from disappearance and appearance experiments and no evidence for ν_μ disappearance has yet been observed. In addition to contributing to a major extension of the Standard Model, the existence of active-sterile neutrino oscillations would also impact the design and planning for future neutrino experiments [6].

The Spallation Neutron Source (SNS) at Oak Ridge National Laboratory [7], built to usher in a new era in neutron research, provides a unique opportunity for US science to perform a definitive search for sterile neutrinos. The 1.4 MW beam power of the SNS is a prodigious source of neutrinos from the decay of pions and muons at rest, and these decays produce a well-specified flux of neutrinos. The low duty factor of the SNS (~ 695 ns beam pulses at 60 Hz) is more than 1000 times less than LAMPF, provides a reduction in cosmic ray backgrounds, and allows the muon-neutrino induced events from pion decay to be separated from the electron-neutrino and anti-muon-neutrino induced events from muon decay.

The OscSNS experiment [8, 9] will make use of this intense source of neutrinos. The OscSNS detector will be centered 60 meters from the SNS target in the backward direction. The cylindrical detector design is based upon the LSND and MiniBooNE detectors and will consist of an 800-ton tank of mineral oil with a small concentration of b-PBD scintillator dissolved in the oil. The tank is covered by approximately 3500 8-inch phototubes, corresponding to a photocathode coverage of 25%. The cylindrical design allows the event rates to be plotted as a function of L/E and allows a direct test for neutrino oscillations and the LSND signal. Furthermore, the relevant neutrino cross sections are known to two percent or better and there is no bias in the neutrino energy reconstruction.

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II. PHYSICS GOALS

Observations of neutrino oscillations, and therefore neutrino mass, have been made by solar-neutrino experiments at a $\Delta m^2 \sim 7.5 \times 10^{-5}$ eV^2, and by atmospheric-neutrino experiments at a $\Delta m^2 \sim 2.5 \times 10^{-3}$ eV^2, where Δm^2 is the difference in mass squared of the two mass eigenstates that predominate in the oscillation [10]. In addition to these observations, the LSND experiment, which took data at Los Alamos National Laboratory (LANSCE) for six years from 1993 to 1998, obtained evidence for $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ oscillations at a $\Delta m^2 \sim 1$ eV^2 [1]. Oscillations at the mass splittings seen by LSND do not fit with well-established oscillation observations from solar and atmospheric experiments. The Standard Model, with only three flavors of neutrinos, cannot accommodate all three observations. Confirmation of LSND-style oscillations would require further non-trivial extensions to the Standard Model.

The MiniBooNE experiment at Fermilab, designed to search for $\nu_\mu \to \nu_e$ and $\bar{\nu}_\mu \to \bar{\nu}_e$ oscillations and to further explore the LSND neutrino oscillation evidence, has presented separate neutrino and antineutrino oscillation results. Combining these results, MiniBooNE observes a 3.8σ excess of events in the 200-1250 MeV oscillation energy range that is consistent with the LSND signal [2]. Many of the beyond-the-Standard-Model explanations of this excess involve sterile neutrinos, which would have a huge impact on astrophysics, supernovae neutrino bursts, dark matter, and the creation of the heaviest elements. Fig. 1 shows the L/E (neutrino proper time) dependence of $\bar{\nu}_\mu \to \bar{\nu}_e$ from LSND and $\bar{\nu}_\mu \to \bar{\nu}_e$ and $\nu_\mu \to \nu_e$ from MiniBooNE. The correspondence between the two experiments is striking. Furthermore, Fig. 2 shows fits to the world neutrino plus antineutrino data that indicate that the world data fit reasonably well to a 3+2 model with three active neutrinos and two sterile neutrinos [5].

The SNS [7] offers many advantages for neutrino oscillation physics, including known neutrino spectra, well understood neutrino cross sections (uncertainties less than a few percent), excellent neutrino energy resolution, low duty factor for cosmic ray background rejection, low beam-induced neutrino background, and a very high neutrino rate of greater than 10^{15}/s from the decay of stopped pions and muons in the Hg beam dump. Stopped pions produce 29.8 MeV mono-energetic ν_μ from $\pi^+ \to \mu^+\nu_\mu$ decay, while stopped muons produce $\bar{\nu}_\mu$ and ν_e up to the 52.8 MeV endpoint from $\mu^+ \to e^+\nu_e\bar{\nu}_\mu$ decay. Note that greater than 99% of π^- and μ^- capture in Hg before they have a chance to decay, so that hardly any neutrinos are produced from either $\pi^- \to \mu^-\bar{\nu}_\mu$ or $\mu^- \to e^-\bar{\nu}_e\nu_\mu$ decay.

The SNS neutrino flux is ideal for probing $\bar{\nu}_\mu \to \bar{\nu}_e$ and $\nu_\mu \to \nu_e$ appearance, as well as ν_μ and ν_e disappearance into sterile neutrinos. The appearance searches both have a two-fold coincidence for the rejection of background. For $\bar{\nu}_\mu \to \bar{\nu}_e$ appearance, the signal is an e^+ in coincidence with a 2.2 MeV γ: $\bar{\nu}_e p \to e^+ n$, followed by $np \to D\gamma$. For $\nu_\mu \to \nu_e$ appearance, the signal is a mono-energetic 12.5 MeV e^- in coincidence with an e^+ from the β decay of the ground state of ^{12}N: $\nu_e\ ^{12}C \to e^-\ ^{12}N_{gs}$, followed by $^{12}N_{gs} \to\ ^{12}Ce^+\nu_e$. The ν_μ disappearance search will detect the prompt 15.11 MeV γ from the neutral-current reaction $\nu_\mu C \to \nu_\mu C^*(15.11)$. This reaction has been measured by the KARMEN experiment, which has determined a cross section that is consistent with theoretical expectations [11]. However, the KARMEN result was measured in a sample of 86 events, and carries a 20% total error. OscSNS will be able to greatly improve upon the statistical and systematic uncertainties of this measurement. If OscSNS observes an event rate from this neutral-current reaction that is less than expected, or if the event rate displays a sinusoidal dependence with distance (L/E can be measured with a resolution of $\sim 1\%$), then this will be evidence for ν_μ oscillations into sterile neutrinos. The ν_e disappearance search will measure the reaction $\nu_e C \to e^- N_{gs}$ followed by N_{gs} beta decay. This reaction is very clean with a very low background due to the two-fold signature. Furthermore, the neutrino energy is approximately equal to the electron energy, so that L/E can be measured with a resolution of $< 5\%$, which allows for a sensitive test for oscillations in the detector.

In addition to the neutrino oscillation searches, OscSNS will also make precision cross section measurements of $\nu_e C \to e^- N_{gs}$ scattering and $\nu e^- \to \nu e^-$ elastic scattering. The former reaction has a well-understood cross section and can be used to normalize the total neutrino flux, while the latter reaction, involving ν_μ, ν_e, and $\bar{\nu}_\mu$, will allow a precision measurement of $\sin^2\theta_W$.

Table I summarizes the expected event sample sizes for the disappearance and appearance oscillation searches, per calendar year, with OscSNS. Fig. 3 shows the expected sensitivity for $\bar{\nu}_e$ appearance after two and six calendar years of run time. The LSND allowed region is fully covered by more than 5σ. The cylindrical design of the OscSNS detector allows for detection of oscillations as a function of L/E, as shown in Fig. 4. Such an observation would prove that any observed excess is due to short-baseline neutrino oscillations, and not due to a misunderstood background. The oscillation sensitivities can be further improved by the construction of a near detector and by the planned construction of a second target station that is located at a longer neutrino baseline.

Acknowledgments

This material is based upon work supported by the U.S. Department of Energy, Office of Science, Office of Nuclear Physics.

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[7] The Spallation Neutron Source (SNS) is an accelerator-based source built in Oak Ridge, Tennessee, by the U.S. DOE, http://sns.gov/. Also see http://www.phy.ornl.gov/workshops/sns2/ for details on the neutrino source and cross section detector ν-SNS.

[8] R. Allen *et al.*, arXiv:1307.7097 [hep-ex] (2013).

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Channel	Background	Signal
Disappearance Search		
$\nu_\mu\ {}^{12}C \to \nu_\mu\ {}^{12}C^*$		
$\nu_e\ {}^{12}C \to \nu_e\ {}^{12}C^*$		
$\bar{\nu_\mu}\ {}^{12}C \to \bar{\nu}_\mu\ {}^{12}C^*$	1060 ± 36	3535 ± 182
$\nu_\mu\ {}^{12}C \to \nu_\mu\ {}^{12}C^*$	224 ± 75	745 ± 42
$\nu_e\ {}^{12}C \to e^-\ {}^{12}N_{gs}$	24 ± 13	2353 ± 123
Appearance Search		
$\bar{\nu}_\mu \to \bar{\nu}_e$: $\bar{\nu}_e\ {}^{12}C \to e^+\ {}^{11}B\ n$		
$\bar{\nu}_\mu \to \bar{\nu}_e$: $\bar{\nu}_e\ p \to e^+\ n$	42 ± 5	120 ± 10
$\nu_\mu \to \nu_e$: $\nu_e\ {}^{12}C \to e^-\ {}^{12}N_{gs}$	12 ± 3	3.5 ± 1.5

TABLE I: Summary of per calendar year event rate predictions for a detector located at the SNS, centered at a distance of 60 meters from the interaction point, at ~150 degrees in the backward direction from the proton beam. The first column is the oscillation channel, the second column is the expected intrinsic background, and the third column is the expected signal for appearance searches and the total number of events for disappearance searches. All event rates account for a 50% detector efficiency, a 50% beam-on efficiency, a fiducial volume of 523 m^3, and are in units of expected events per calendar year. Appearance signal estimates assume a 0.26% oscillation probability.

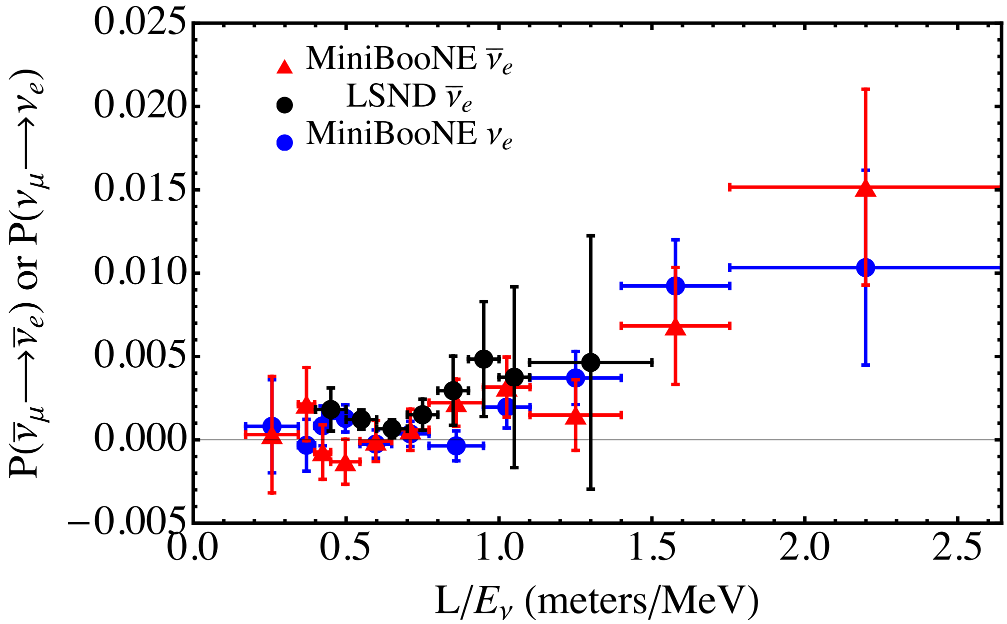

FIG. 1: The probability of $\bar{\nu}_\mu \to \bar{\nu}_e$ from LSND and $\bar{\nu}_\mu \to \bar{\nu}_e$ and $\nu_\mu \to \nu_e$ from MiniBooNE as a function of the neutrino proper time.

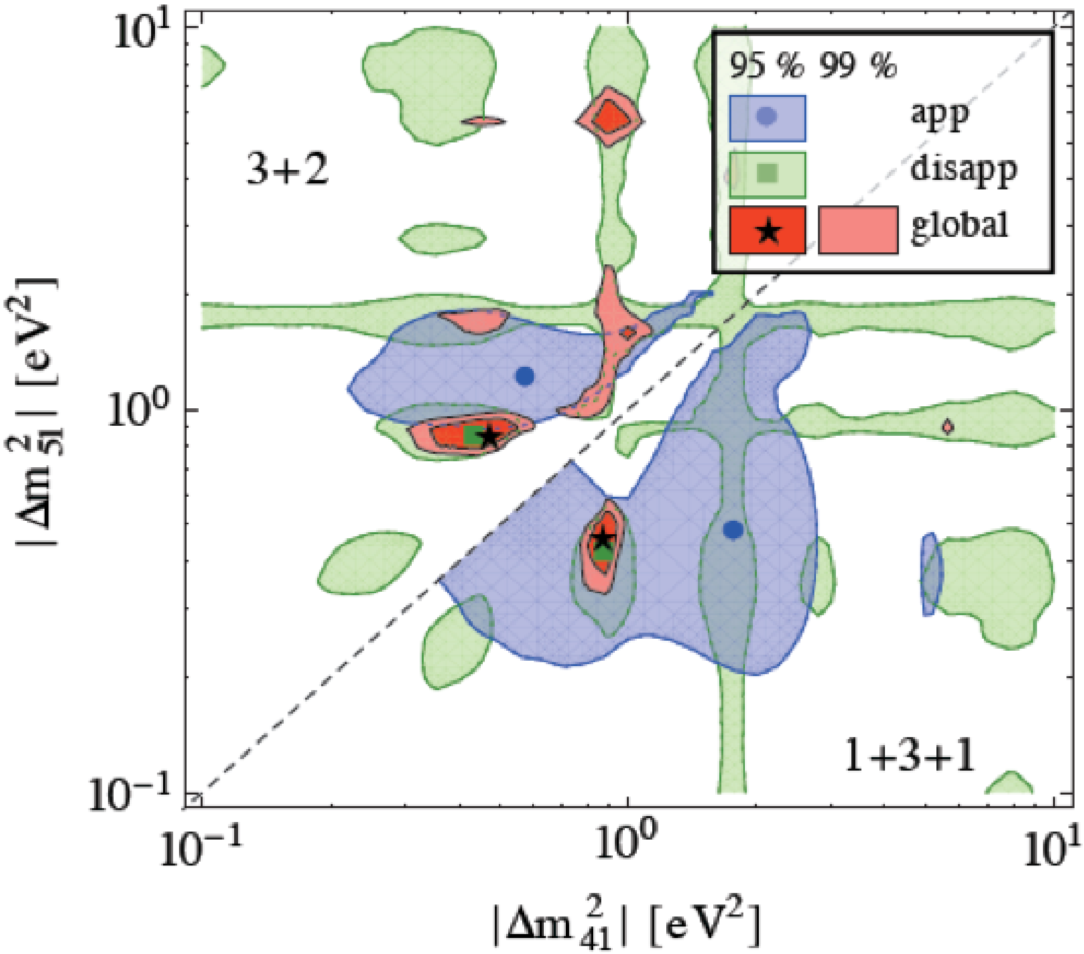

FIG. 2: A global fit to the world neutrino plus antineutrino data indicates that the world data fit reasonably well to a 3+2 model with three active neutrinos plus two sterile neutrinos [5].

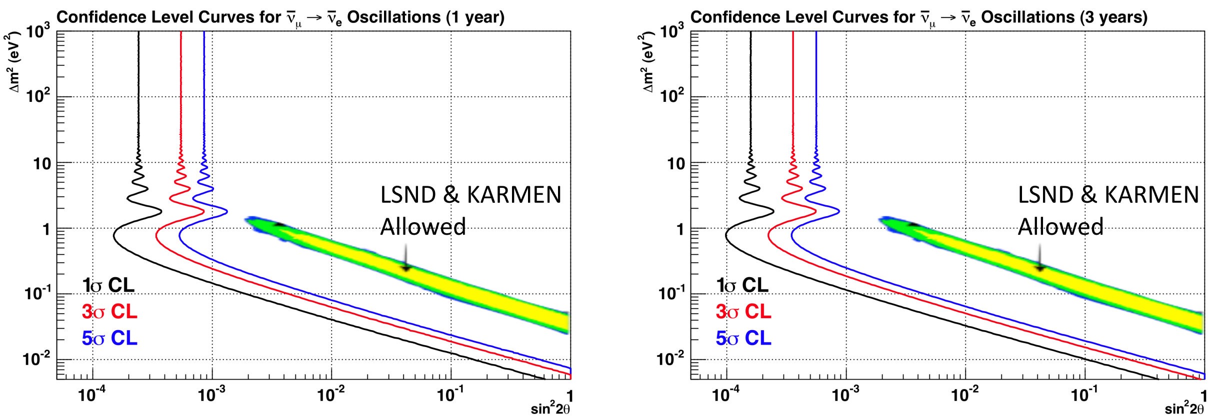

FIG. 3: The OscSNS sensitivity curves for the simulated sensitivity to $\bar{\nu}_\mu \to \bar{\nu}_e$ oscillations after two (left) and six (right) *calendar* years of operation, assuming a 50% beam on-time (one and three years of running at 100% beam-on). Note that it has more than 5σ sensitivity to the LSND result in 2 years.

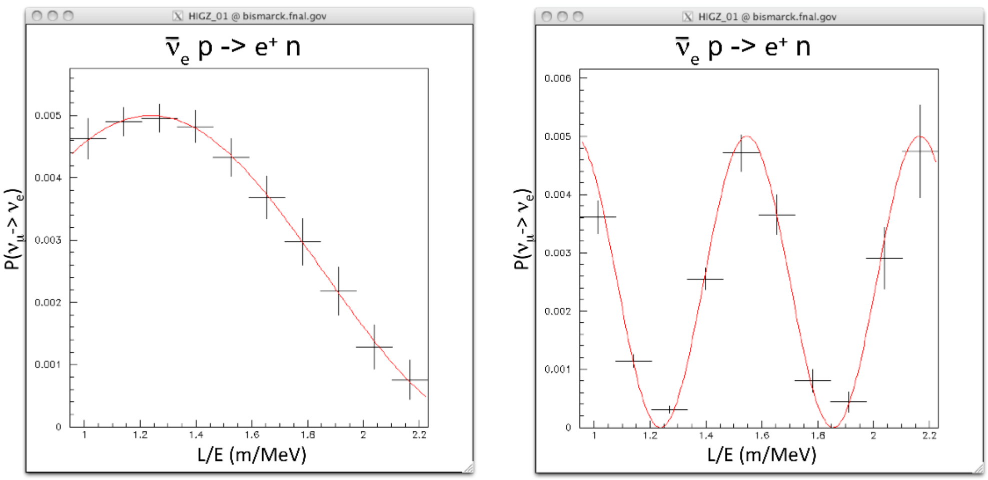

FIG. 4: The expected oscillation probability from $\bar{\nu}_e$ appearance as a function of L/E for $\sin^2 2\theta = 0.005$ and $\Delta m^2 = 1$ eV^2 (left plot) and $\Delta m^2 = 4$ eV^2 (right plot). The plot assumes ten calendar years of data collection at 50% beam live-time.