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SHORT-BASELINE NEUTRINO FOCUS GROUP REPORT

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1. INTRODUCTION

Neutrino oscillations have been firmly established by experiments that measure solar neutrinos, atmospheric neutrinos, reactor antineutrinos, and accelerator-produced neutrinos and antineutrinos. To a first approximation, three-flavor mixing provides a good description of the neutrino oscillation phenomenology. Within the three-flavor mixing framework there are three mixing angles ($\theta_{12}, \theta_{23}, \theta_{13}$), two independent mass splittings characterized by Δm^2_{21} and Δm^2_{31} (where $\Delta m^2_{ij} = m^2_i - m^2_j$), and one CP phase δ. All of these parameters have been measured except the sign of Δm^2_{31} and the phase δ. The long-baseline neutrino program is focused on measuring these unknown parameters, and hence determining the ordering of the neutrino masses, and seeing if neutrino oscillations violate CP-symmetry.

The three-flavor mixing framework provides an elegant and economical way to describe neutrino oscillations; it adds neutrino masses and lepton mixing to the Standard Model, but nothing more. However, there are some indications, at the level of two to four standard deviations, that three-flavor mixing might not be the whole story. Individually, these tensions with three-flavor mixing do not provide definitive evidence for new physics. Some or all of them may be due to statistical fluctuations and/or systematic effects. Taken together, the experimental evidence for the presence or absence of neutrino flavor transitions with a frequency characterized by *L/E* ~ 1 m/MeV (which corresponds to Δm^2_{i4} ~ 1 eV^2) is inconclusive. The anomalies are intriguing, and persistent enough to warrant definitive investigation.

In response to this situation, and the need to define a strategic plan for short-baseline neutrino physics at Fermilab, in December 2011 the Fermilab Directorate formed the “Short-Baseline Neutrino Focus Group”. The membership of the group and its charge can be found in Appendices 1 and 2. The Directorate asked the group to consider new detectors and/or new types of neutrino source that would lead to a definitive resolution of the existing anomalies. The group was asked specifically to:

1. Evaluate to what extent the ongoing and planned neutrino experiments will be able to resolve the origin of each of the couple of sigma tensions with three-flavor mixing. Identify any additional measurements that might be needed, and options for making these measurements.

2. Compare with competing facilities the future capabilities at Fermilab for supporting a short-baseline neutrino program to definitively resolve the present anomalies, and suggest what the optimal short-baseline neutrino program might be beyond the presently approved and running experiments.

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1.1 Organization and Strategy

The Focus Group had its initial meeting early January 2012, and organized its membership into the 4 working groups listed in Appendix 3. Each working group had a facilitator that organized working group meetings and assignments. In addition, the overall Focus Group held general meetings to discuss progress, plans, and conclusions. The webpage for the Focus Group can be found: http://sbl-neutrinos.fnal.gov/ .

An important Focus Group activity has been to solicit and digest input from the community in order to more fully understand the present tensions, the likely impact of the ongoing approved program, and the range of ideas for future experiments. In 2011 there were three workshops in the U.S. that provided the community with an opportunity to present and discuss the tensions with three-flavor mixing, and possible future experiments:

- **Short-Baseline Neutrino Workshop**, FNAL, May 12-14, 2011.
- **Fundamental Physics at the Intensity Frontier**, Rockville, MD, Nov. 30 – Dec. 2, 2011.
- **Sterile Neutrinos at the Crossroads**, Blacksburg, VA, Sep. 25-28, 2011.

The organizers of the last two of these workshops produced respectively a report and a white paper that provided a valuable starting point for the Focus Group. In addition to these prior meetings, the Focus Group organized an all-day workshop to enable further dialogue with the community and an opportunity for proponents of possible future experiments to present and update their ideas. The resulting *Future Short-Baseline Neutrino Experiments: Needs and Options Workshop (*https://indico.fnal.gov/conferenceDisplay.py?ovw=True&confId=5273*)* was held at Fermilab on March 21st, 2012. With 112 participants, the meeting provided valuable input.

The Focus Group produced an interim report in April 2012. The present "Final Report" updates this earlier document with the addition of conclusions, recommendations, and a suggested "Strategic Plan" for short-baseline experiments at Fermilab.

2. TENSIONS WITH THREE-FLAVOR MIXING AND THEIR INTERPRETATION

The following summarizes the present global picture, including the deviations from three-flavor mixing, and attempts to understand these hints in terms of new physics.

2.1 Summary of the Tensions

The tensions come from reactor antineutrino measurements, radioactive source measurements, and accelerator-based neutrino and antineutrino measurements at short baselines:

- A re-evaluation of the $\bar{\nu}_e$ flux from nuclear reactors implies that short-baseline reactor experiments observe a 6% deficit (at the 2-3σ level) of electron antineutrinos. The experiments in question use baselines between 10 m and 1 km, and are sensitive to antineutrinos with energies in the 2–8 MeV range. For this range of baselines *L* and energies *E*, the “reactor anomaly” is consistent with an effect that is independent of *L* and *E* (or the ratio *L/E*), and can be interpreted as a hint for $\bar{\nu}_e$ disappearance at short-baselines on timescales characterized by *L/E* values between a few and a few hundred m/MeV.

- Calibration data from the gallium solar neutrino experiments, which make use of intense radioactive ^{51}Cr and ^{37}Ar electron capture sources, hint at the disappearance of ν_e at short-baselines. These experiments study neutrinos with energies below 1 MeV and probe baselines around 1 m, and hence correspond to values of *L/E* around 1 m/MeV. This effect is at the 2σ level.

- Data from the LSND experiment provide evidence for $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ transitions at short-baselines. LSND used a baseline *L* around 30 m and was sensitive to antineutrino energies of tens of MeV, spanning *L/E* values between 0.2 m/MeV and 3 m/MeV. The LSND excess, expressed as a flavor conversion probability, is depicted as a function of *L/E* in Fig. 1. The excess of $\overline{\nu_e}$ events above background corresponds a $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ conversion probability of around 0.2%. The no-conversion hypothesis is ruled out at over 3σ. The data also hint that the conversion probability might depend on *L/E*. A second experiment, KARMEN, with sensitivity similar to that of LSND, took data with a shorter baseline (*L* ~ 18 m) and did not observe a $\overline{\nu_e}$ excess, suggesting that the phenomenon might depend on *L*.

- The MiniBooNE experiment was conducted to test the LSND anomaly under the assumption that the new physics is a function of *L/E*. This assumption is valid as long as the anomaly is related to a property of the space-time evolution of the neutrino state (e.g. flavor oscillations or a finite neutrino lifetime). MiniBooNE used a baseline *L* ~ 500 m and neutrino energies around hundreds of MeV, spanning the same *L/E* region as LSND. MiniBooNE took both neutrino and antineutrino data. The MiniBooNE neutrino data indicate an excess of ν_e events above background at low energies (*E* < 0.5 GeV), which is evident in the highest *L/E* bins (Fig. 2). This is referred to as the MiniBooNE low energy excess. Note that these low energy bins are outside the *L/E* range probed by the LSND experiment, and are in a region where background events are most abundant. The low energy excess may be due to an as yet-to-be-identified standard model background including, for example, an unexpectedly high rate of photons from certain exclusive neutral current processes. This possibility will be explored by the MicroBooNE experiment. At lower *L/E* the MiniBooNE neutrino data are consistent with the null hypothesis, suggesting that if the LSND antineutrino anomaly is due to new physics, the new physics might not conserve CP.

- The MiniBooNE antineutrino data (Fig. 1) is consistent with the LSND antineutrino data and, excluding the two low energy bins, is only marginally consistent with the null hypothesis. Taken together, the LSND and MiniBooNE antineutrino data provide evidence for new physics at greater than 3σ.

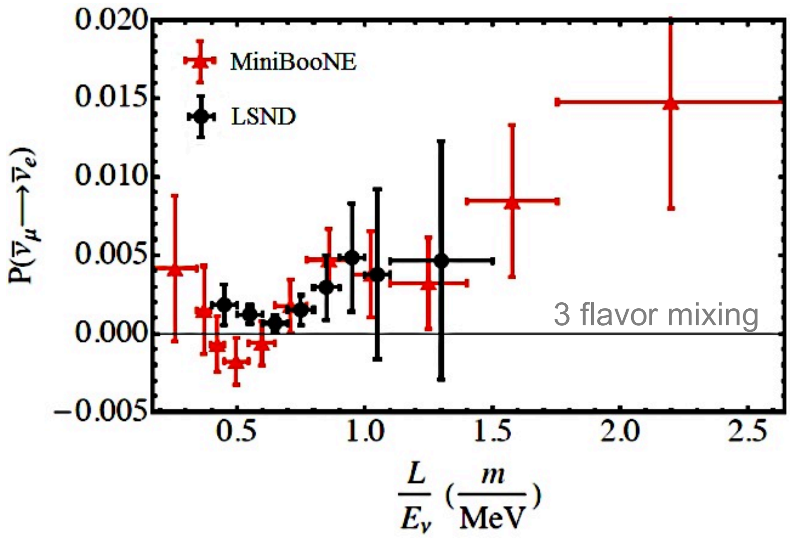

Figure 1: LSND and MiniBooNE antineutrino data, showing evidence for flavor transitions above the three-flavor mixing null expectation.

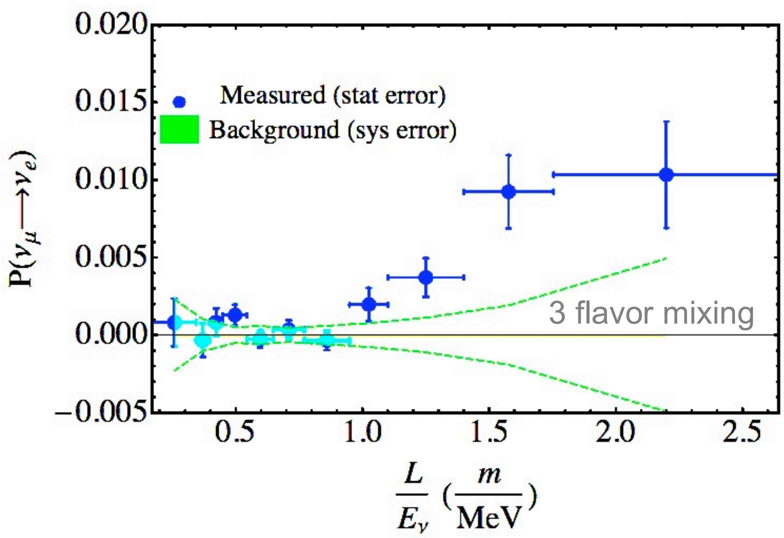

Figure 2: MiniBooNE neutrino data, showing evidence for an excess of electron-like events at low energies (E < 0.5 GeV), and therefore large L/E.

In addition, cosmological measurements provide curious hints that the number of relativistic degrees of freedom is larger than dictated by the standard model. The measured ^{4}He and D abundances, which in Big Bang Nucleosynthesis (BBN) calculations depend upon the expansion rate of the early Universe, and hence on the number of relativistic degrees of freedom, are consistent with an effective neutrino number that lies between 3 and 4. Combinations of lower-redshift cosmological observables, including precision measurements of spatial correlations in the cosmic microwave background radiation temperature, also point to an effective neutrino number that is more consistent with 4 than 3. More generally, these data suggest that the ultra-relativistic component of the energy density of the early universe might be higher than expected. A fourth light neutrino in thermal equilibrium before BBN is one candidate explanation. At the same time, similar data, including studies of large-scale structure, require all light “neutrino” degrees of freedom to be lighter than a fraction of an eV. Hence, if there is evidence for new neutrinos from cosmology, they may not be able to provide an explanation of the short-baseline tensions with three-flavor mixing. More cosmological data, especially those from Planck, are expected to qualitatively improve the cosmological constraints on new neutrino states. If new neutrino states that are in conflict with the cosmological constraints are discovered by terrestrial experiments, it might force a change in the Standard Cosmology, and hence in our understanding of the early Universe.

2.2 Interpretation as New Physics

There is no model-independent way of relating the various short-baseline anomalies, and hence there remains the logical possibility that they are unrelated phenomena. However, it is much more interesting to postulate that subsets of the observed tensions with three-flavor mixing are different manifestations of the same underlying new physics, and in our opinion, this possibility provides the strongest motivation for definitively investigating the source of the anomalies. Assuming the new physics phenomenon depends on *L/E*, and taking all anomalies at face value, it would appear that the new physics is strongly CP- violating. Furthermore, since the reactor experiments and LSND probe similar *L/E* ranges, there remains the possibility that the same phenomenon explains anti-ν_e disappearance and anti-ν_μ to anti-ν_e conversion. Finally, if the new physics requires the introduction of new degrees of freedom, one may also hope to address the various cosmological hints.

The tensions can be interpreted as evidence for one or more new light neutrino states, with masses below a few eV. LEP data allow only three light neutrino weak-eigenstates, so the new orthogonal state(s) do not participate in charged-current or neutral-current weak-interactions, and are hence dubbed sterile. A scenario with *n* new neutrino mass eigenstates is referred to as a 3 + *n* scenario. Both 3 + 1 and 3 + 2 scenarios provide mediocre fits to the global neutrino data, and 3 + 3 and “higher” scenarios, it has been argued, do not fare significantly better. The relatively poor fits are a consequence of other neutrino data that provide no evidence for new neutrinos at 1 eV. These include the standard neutrino oscillation data (solar and atmospheric, MINOS, K2K, and KamLAND) and short-baseline searches for the disappearance of ν_e and ν_μ (and their antiparticles). In addition, 3 + 1 scenarios do not violate CP at the appropriate *L/E* (for which there is effectively just one mass splitting), and consequently have difficulty accommodating the CP violation implied by the presence of an antineutrino signal (LSND and MiniBooNE), and absence of a neutrino signal (MiniBooNE). Given this, 3 + 2 scenarios (and “higher”) are interesting because they can resolve the MiniBooNE neutrinos versus LSND/MiniBooNE antineutrinos conundrum by making use of new CP-violating phases that are observable in short-baseline experiments. The argument has also been made that the 3 + 2 scenario provides a qualitatively better fit to all data than the 3 + 1 scenario.

Other new physics — new neutrino interactions, violation of fundamental symmetries, etc. — can either replace the 3 + *n* models as candidate explanations for the short-baseline anomalies, or can help alleviate some of the tension with the neutrino data or between the neutrino data and cosmological observables. It is fair to say, however, that no compelling new physics model has arisen, and that, at least for phenomenological purposes, the 3 + 1 and, especially, the 3 + 2 scenarios are considered the simplest, more robust description of what may be going on.

Ultimately, we are faced with a puzzle that must be resolved experimentally.

Using the light-sterile-neutrino model as a guide, it is possible to identify definitive tests of the short-baseline anomalies. These include better than per mille searches for $\nu_\mu \leftrightarrow \nu_e$ transitions at short baselines, and percent-level searches for ν_μ and ν_e disappearance. Slightly more model dependent arguments point to searches for ν_τ appearance, at the per-mille level as complementary, nontrivial sources of information. In more detail, the main goal is to (a) look for $\nu_\mu \leftrightarrow \nu_e$ at *L/E* values around 1 m/MeV with precision that is qualitatively superior to that obtained by both LSND and MiniBooNE, and (b) measure $\nu_e \rightarrow \nu_e$ and $\nu_\mu \rightarrow \nu_\mu$ survival probabilities at *L/E* values around 1 m/MeV at around the percent level. A good rule of thumb is as follows: appearance probabilities of order ε^2 imply disappearance rates around ε. Note that the observation of the *L/E*-dependence will be important to establish oscillations as the underlying physics model. Finally, another phenomenological feature specific to sterile neutrino oscillations is that the oscillation signatures should also exist with the same strength in neutral current detection experiments.

2012-2013	***2013-2014***	***2014-2017***
Appearance:		
MiniBooNE anti-ν_e (x2 more data)	ICARUS ν_e	MicroBooNE ν_e
MiniBooNE ν_e, anti-ν_e combination	T2K near detector ν_e	NOvA near detector ν_e, anti-ν_e
Disappearance:		
MiniBooNE/SciBooNE joint anti-ν_μ	IceCube ν_μ and anti-ν_μ	MicroBooNE ν_μ MINOS+ ν_μ
Other:		
reactor flux calculations	radioactive source exps. Planck results	

Table I: List of expected measurements from on-going and near-term approved experiments.

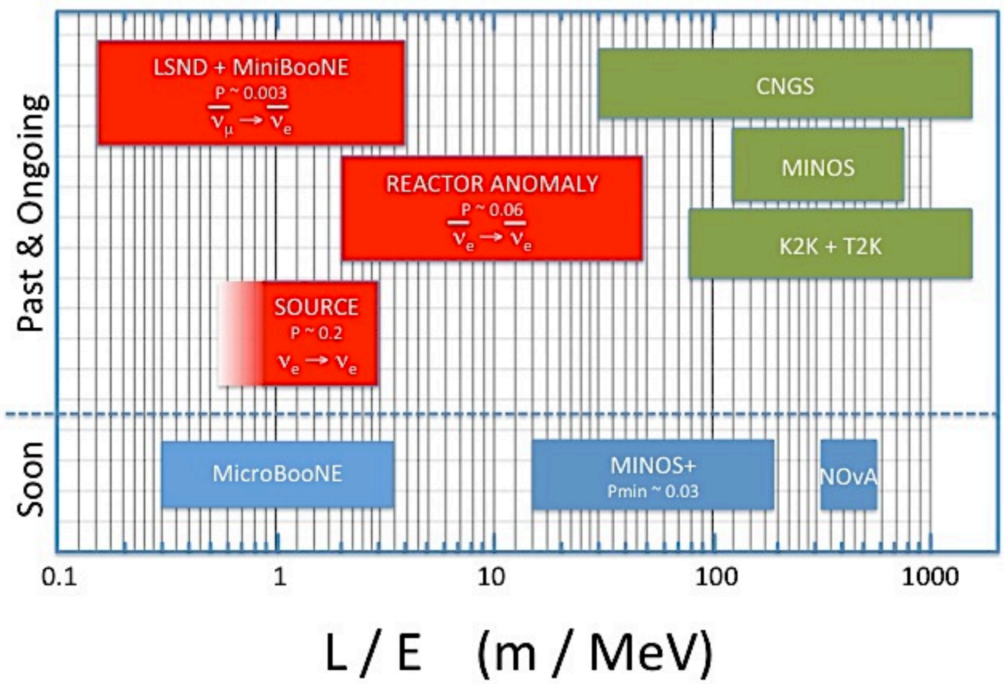

Figure 3: The L/E coverage for the next generation of neutrino experiments at Fermilab (blue) compared with the coverage of the short-baseline experiments reporting anomalies (red) and recent long-baseline experiments (green).

3. INPUT FROM UPCOMING MEASUREMENTS

A variety of running and approved experiments are expected to add new information that may help us interpret the present tensions with the three-flavor mixing and contribute to the search for light sterile neutrinos at the $\Delta m^2 \sim 1\text{eV}^2$ scale. Table 1 lists the anticipated experimental information as a function of time, broken up into near-term (2012-2013), mid-term (2013-2014), and longer-term (2014-2017) intervals.

Different upcoming measurements will cover different regions of *L/E* (Fig. 3). Together, these measurements will explore oscillations driven by splittings Δm^2 from 0.002 eV^2 to effectively infinity.

In the very near-term, final results from MiniBooNE and SciBooNE will add to our knowledge of the accelerator-based tensions. By the end of 2014, results from ICARUS and the T2K near detector might also contribute to our understanding of the tensions between LSND/MiniBooNE results and three-flavor mixing. It is also possible that MINERvA's fine grained tracking would help in this area and on this timescale. One cannot predict the impact these unknown results will have on the programmatic short-baseline decisions of the community, but the new measurements will not cover the LSND/MiniBooNE preferred region of sterile-neutrino parameter space with 5σ precision. In addition to the accelerator-based experiments, during

2014 we can anticipate the release of Planck data, and the possibility of results from radioactive source experiments. The Planck data are expected to clarify the constraints on, and likelihood of, extra neutrino degrees of freedom assuming the standard ΛCDM cosmology. Results from Planck and/or radioactive source experiments in 2014 could either strengthen or weaken the evidence for a sterile neutrino interpretation of the present anomalies, but do not directly test the LSND/MiniBooNE anomaly.

In the period 2014-2017 two accelerator-based experiments, both at Fermilab, will further add to our knowledge:

i) MINOS+ : The NOvA-era NuMI beam will produce a large flux of high-energy ν_μ and anti-ν_μ at the MINOS near and far detectors. MINOS+ will exploit this beam with the present MINOS detector to search for ν_μ and anti-ν_μ disappearance with a sensitivity that surpasses the existing MINOS data. The range of *L/E* values covered by MINOS+ overlaps the range covered by the reactor experiments reporting evidence for anti-ν_e disappearance. MINOS+ can also measure neutral current interactions in the near and far detectors, and look for the disappearance of active neutrinos, a clear signature of sterile neutrino oscillations. If the MINOS+ result is a limit, rather than a signal, then combining the ν_μ disappearance limit with reactor anti-ν_e disappearance limits will enable, for a 3+1 model, a limit to be placed on $\nu_\mu \rightarrow \nu_e$. For example, combining the expected sensitivity of MINOS+ with BUGEY results, the LSND preferred region of sterile neutrino parameter space for $\Delta m^2 < 10$ eV^2 would be covered at greater than 90% C.L.

ii) MicroBooNE: This new experiment is under construction, and will utilize a 170-ton liquid Argon Time Projection Chamber (LArTPC), with a fiducial volume of 60 tons, located in the Booster neutrino beam, 470m from the target. The experiment will measure low energy neutrino cross-sections, and investigate the low energy electron-like excess observed by the MiniBooNE experiment. Due to it's high spatial resolution the detector can separate final state electrons from photons. If the low-energy excess is really due to ν_e events, and hence events tagged by an electron, MicroBooNE is expected to confirm this at the 5σ level (with 6×10^{20} POT in neutrino running). On the other hand, if the excess is associated with events tagged by a photon, MicroBooNE is expected to determine this at the 4σ level.

In addition to MINOS+ and MicroBooNE, data from the NOvA near detector and further data from MINERvA, will also add to our understanding of neutrino interactions and cross-sections.

In summary, in the coming years we anticipate a range of experimental results that can inform our interpretation of the present anomalies. However, none of the approved and/or running experiments will directly test $\nu_\mu \rightarrow \nu_e$ transitions or the anti-neutrino counterpart over the full LSND/MiniBooNE preferred region of sterile-neutrino parameter space with 5σ precision.

4. REQUIREMENTS FOR LONGER-TERM DEFINITIVE EXPERIMENTS

In the following we limit ourselves to future accelerator-based experiments, since these are the ones most relevant to forming a strategic short-baseline neutrino plan for Fermilab. Understanding and articulating the requirements for these future experiments is central to constructing a defensible strategic plan. To pin down the requirements, the following questions must be addressed for each component of the plan: (i) What measure(s) are to be used to characterize the sensitivity of a particular experiment? (ii) What statistical precision must the experiment achieve to be definitive? (iii) What systematic precision must be achieved to be definitive?

4.1 Measures of Sensitivity

If some or all of the present tensions are due to new physics, the distributions or variables that are most sensitive to the new physics depend upon the nature of the physics. If that new physics involves sterile neutrinos, then the two-parameter space $(\sin^2 2\theta,\ \Delta m^2)$ is appropriate (for one effective sterile neutrino). It has therefore become popular to characterize the sensitivity of short-baseline experiments by the region of the $(\sin^2 2\theta,\ \Delta m^2)$-plane covered with a given significance. However, more general distributions that are closer to the experimentally measured parameters are also of interest: in particular, the probabilities for flavor-appearance or flavor-disappearance as functions of neutrino travel distance *L*, energy *E*, and time (i.e. *L/E*).

A "definitive" program would be one that could definitively discover an effect at the level indicated by the present tensions in any of the 4 plots: $(\sin^2 2\theta,\ \Delta m^2)$, *P vs L, P vs E,* and *P vs L/E*.

4.2 Statistical Precision

Within the neutrino community, a widely accepted standard for defining the precision needed for a result to be judged "definitive" is 5 standard deviations. The LSND / MiniBooNE results indicate $P(\bar{\nu}_\mu \to \bar{\nu}_e)$ ~ 0.003 for appropriate *L/E*. This implies a desired 1σ sensitivity σ_p ~ 0.0006 for each *L/E* bin in the range of interest. Note that the disappearance probability could be considerably larger, and therefore the 1σ sensitivity could still be interesting (although perhaps not definitive) at the 1% level. Since the main LSND/MiniBooNE tension is seen in the antineutrino data, to definitively resolve this tension, the required precision for the appearance channel using conventional neutrino beams must be achieved with the statistically more challenging antineutrino measurements (i.e. $\bar{\nu}_\mu \to \bar{\nu}_e$). Assuming CPT-invariance, with a less conventional beam that permits a search for $\nu_e \to \nu_\mu$ transitions, the measurement must be made in the neutrino channel.

The factors that determine the statistical precision, and that need to be understood and quantified at the proposal stage, are:

A. Detector Mass and Running Time: Recent history has shown that between proposal and construction, fiscal limitations can result in a significant reduction in detector mass. This "de-scoping" can, in principle, be compensated by longer running time.

B. Signal Efficiency: To ensure "definitive" sensitivity, signal efficiencies should be based on prior experiments or, for new technologies, dedicated measurements.

C. Background Rates: Experiments with statistical precision beyond that already achieved are vulnerable to unanticipated backgrounds that reduce the sensitivity to the signal.

D. Protons on Target: The total number of protons on target per year depends upon the primary beam intensity achieved, the up-time (number of operational seconds / year) for the accelerator complex, beamline components (e.g. target and horns), and detector. The recent historical record can inform assumptions about the difference between what can be achieved in principle, and what is likely to be achieved in practice.

Each of these factors has an associated uncertainty that can be mapped into a reduction in experimental sensitivity. To be able to defend, at the time of proposal, the statistical precision that an experiment might achieve, it will be important to be able to present the result of each of these uncertainties on the achievable precision, based upon realistic assumptions. This will help quantify the risk to the experimental sensitivity, and also respond to the widespread impression that to achieve 5σ sensitivity, an experiment must at the proposal stage have much greater than 5σ sensitivity.

4.3 Systematic Precision

Systematic uncertainties are likely to play an important, and perhaps dominant, role in the achievable sensitivities for future short-baseline accelerator-based experiments. Those uncertainties include uncertainties on fluxes and cross-sections (Section 3), fiducial mass, signal efficiencies, and background rates. Given the need for definitive experiments searching for very small effects with systematic uncertainties limiting, or being close to limiting, the sensitivity, great attention must be paid to controlling and quantifying the systematic effects, and this increased attention should already be manifest at the proposal stage with each uncertainty being quantified and defended based upon measurements.

It is desirable that proponents show, at the proposal stage, not only the uncertainties and their impact, but also the uncertainty on the uncertainties.

In the last few years it has been shown that two detectors at different baselines can be used to reduce many of the systematic uncertainties. It is likely that the next round of short-baseline experiments will need either two or more detectors, or a single long detector that can measure event rates as a function of *L*.

At low energies, in the region where uncertainties on the backgrounds might be large, it is desirable that the detector can distinguish between electrons and photons.

It is also desirable that the detector be capable of distinguishing ν_μ from anti-ν_μ charged-current interactions.

	π^+ ***decay at rest***	$\pi^\pm$ ***decay in flight***	$\mu^\pm$ ***decay in flight***
Measurement	$\bar{\nu}_\mu \rightarrow \bar{\nu}_e$	$\nu_\mu \rightarrow \nu_e$ $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ $\nu_\mu \rightarrow \nu_\mu$ $\bar{\nu}_\mu \rightarrow \bar{\nu}_\mu$	$\nu_e \rightarrow \nu_\mu$ $\bar{\nu}_e \rightarrow \bar{\nu}_\mu$ $\nu_\mu \rightarrow \nu_\mu$ $\bar{\nu}_\mu \rightarrow \bar{\nu}_\mu$
Energy	<~ 50 MeV	~0.2-3 GeV	~0.2-3 GeV
Detection mode	inverse β decay	ν -nucleus scattering (QE and other)	ν -nucleus scattering (QE and other)
Flux uncertainty	good (%-level)	poor (10's-of-% level)	good (%-level)
Cross-section uncertainty	good (%-level) (for free targets)	poor (10's-of-% level)	poor (10's-of-% level)
Example	LSND	MiniBooNE	νSTORM (proposed)

Table 2: Relevant accelerator-based neutrino sources, their energy range, predominant signal detection mode, and general state of flux and cross section knowledge.

5. CROSS-SECTIONS AND FLUXES

Neutrino oscillation experiments measure the rate of neutrino events in their detectors. This rate is a product of the neutrino flux, neutrino interaction cross-sections, and detector performance. Hence, neutrino fluxes and cross-sections play a crucial role in the interpretation of neutrino oscillation data. For short-baseline experiments, knowledge of the flux and interaction cross-sections for both the relevant signal and background channels are important. Here, we focus on three main questions:

(1) Which neutrino cross-sections and fluxes are important for short-baseline neutrino oscillation measurements?

(2) What is the current state of knowledge on these fluxes and cross-sections?

(3) What additional information on neutrino fluxes and cross-sections might we need to enable future definitive short-baseline experiments?

In the following, we limit ourselves to accelerator-based options since these are the most relevant for future short-baseline experiments at Fermilab.

5.1 Relevant Neutrino Fluxes and Cross-Sections

The fluxes and cross-sections relevant to a given short-baseline experiment depend on the neutrino source, the neutrino energy, and the nuclear target. Table 2 lists the attributes of the three main accelerator-based sources generally considered for short-baseline experiments: stopped pions, and decay-in-flight pion and muon beams. Also listed for each case is the general state of knowledge on neutrino cross-sections and fluxes.

In general, neutrino fluxes are less uncertain if they result from decay-at-rest pion sources or muon decay sources. In those cases, fluxes can be determined to a few %. If the flux and/or cross-section knowledge is poor, the experiment must rely on other techniques to help constrain expected signal and background rates. This may include internal constraints from processes measured in the experiment itself (from a near detector or otherwise) and/or external measurements from other experiments. If a well-known free scattering process, such as inverse β-decay ($\bar{\nu}_e + p \rightarrow e^+ n$), can be used to identify signal events, then nuclear effects are absent and cross-section uncertainties are substantially reduced.

Nuclear effects significantly complicate our understanding of neutrino interactions; hence experiments that use neutrino-nucleus scattering (as opposed to free target scattering) for their signal detection must contend with a myriad of effects that can alter the observed topologies and event rates. We have identified three specific areas of concern for short-baseline ν_e appearance searches:

(1) How well do we know the relative ν_e / ν_μ and $\bar{\nu}$ / ν cross-section ratios as a function of energy? There are newly appreciated sources of nuclear dynamics that can alter our expectations. These arise because a neutrino can scatter off of a strongly-correlated pair of nucleons in a nucleus. It is not entirely clear to what extent such effects impact ν_e interactions differently from ν_μ interactions. There are also varying predictions for what impact these effects have on ν vs. $\bar{\nu}$.

(2) How well can we reconstruct the incoming neutrino energy when scattering off a nuclear target? Here too, nucleon-correlation effects can impact the determination of the neutrino energy inferred from the observed final-state lepton kinematics.

(3) Are there un-modeled sources of neutrino neutral current photon production that can create additional backgrounds to ν_e appearance searches? Known sources of photon production from radiative decays of various baryonic resonances are simulated, but additional possible Standard Model sources have recently surfaced in the literature.

The answers to these questions are not yet known but have been the topic of numerous theoretical papers over the course of the past year. New short-baseline experiment proposals should quantify the potential impact of the above effects on their anticipated sensitivities.

EXPERIMENT	***APPROX. NEUTRINO ENERGY RANGE***	***TARGET***
MiniBooNE	0.2-2 GeV (BNB)	CH_2
SciBooNE	0.2-2 GeV (BNB)	CH
MicroBooNE	0.2-2 GeV (BNB)	Ar
T2K near detector	0.2-2 GeV (JPARC)	C, H_2O
ArgoNeuT	1-20 GeV (NuMI)	Ar
MINERvA	1-20 GeV (NuMI)	He, C, H_2O, Fe, Pb
NOvA near detector	1-4 GeV (NuMI off-axis)	C
NOMAD	3-100 GeV (CERN)	C
ICARUS	0.5-10 GeV (CERN)	Ar

Table 3: List of currently running or approved experiments that will produce additional neutrino cross-section measurements in the coming years.

5.2 Upcoming Measurements and Opportunities

Over the coming years, results from a variety of running and/or soon-to-be-running neutrino cross-section measuring experiments are anticipated. Table 3 summarizes these experiments and their attributes. We have identified several additional future initiatives that could provide further input:

- Upgrades to the MINERvA experiment (H_2, D_2 targets);
- Addition of a fine-grained detector in the NOvA off-axis beam (SciNOvA);
- Construction of a muon storage ring to precisely measure ν_e and $\bar{\nu}_e$ cross-sections with a well-known beam source;
- Upgrades to the MIPP experiment and/or additional running of NA61/SHINE for improved hadro-production measurements.

Since the ability of future short-baseline neutrino experiments to discover or exclude the existence of sterile neutrinos may ultimately be limited by cross-section and flux uncertainties, the impact of these uncertainties on the sensitivity of any new short-baseline experiment should be spelled out in the proposal, together with an assessment of the need for new cross-section and/or particle production measurements beyond those currently planned.

6. EXPERIMENTAL OPTIONS FOR RESOLVING THE ANOMALIES

Table 4 lists the various experimental options that have been presented and discussed at the March 21st workshop and/or the Focus Group working sub-group meetings. It is clear that the community has many ideas about how to proceed, and that those ideas span all of the neutrino source types: radioactive sources, reactors, and accelerator-based sources.

6.1 Radioactive Source Experiments

Radioactive source experiments are being investigated as potential tests for light sterile neutrinos. Typically this technique requires a low background underground setting. The sources can be either β-decay ($\bar{\nu}_e$ or ν_e) or electron capture (mono-energetic ν_e). The neutrinos are detected via inverse neutron decay, ν_e elastic, or charge current interactions. The experiment is sensitive to neutrino disappearance. The very short baselines facilitate measuring the variation of neutrino rates as a function of distance. There are also proposals to detect coherent neutral current reactions on nuclei using technologies developed for Dark Matter searches. To date, this type of experiment has suffered from low statistics, however, with larger detectors and stronger sources, it could be made into a precise measurement. Note that electron capture sources produce a mono-energetic neutrino so that a measurement of the neutrino interaction rate as a function of distance would determine the oscillation parameters. Table 5 summarizes the presently proposed “long-lived” source experiments. Figure 4 shows that anticipated sensitivities cover the region of sterile neutrino parameter space indicated by the reactor anomaly.

Radioactive Source	
Elastic Scattering	Borexino (ν & $\bar{\nu}$), SNO+Cr
Charged Current	LENS, Baksan, Ce-LAND, Borexino, Daya Bay
Neutral Current	RICOCHET: coherent scattering with bolometers
Reactors	
SCRAAM	Reactors with small core: Bugey, SONGS, ATR
Stereo	Reactor with small core. LS doped with Gd, L = 8-10 m.
RICOCHET - Reactors	Coherent scattering with bolometers
Atmospheric Neutrinos with L/E ~ 1 m/MeV	
Fe Calorimeter	ICAL or INO
LAr Detector	
Other	ICECUBE
Accelerators: Decay at Rest	
OscSNS	Off-axis, ORNL or FNAL
LSND Reloaded	Super-K with Gd & cyclotron
IsoDAR	60 MeV cyclotron, ^{12}B &/or ^{8}Li decay at KamLAND
RICOCHET - DAR	Coherent scattering with bolometers
Accelerators: Decay in Flight	
BooNE	Two detectors
MicroBooNE + LAr	Two LAr TPC's (LArLAr)
NOvA Short-Baseline	1-2 km off-axis detector(s), also SciNOvA
Nu-tau appearance	With L/E ~ 1 m/MeV
Muon Storage Ring	pions captured within the ring, then decay to muons wh remain captured in the ring
Entry-Level Neutrino Factory	Higher intensity than muon storage ring
Neutrino Factory	Full "International Design Study for a NF" Design

Table 4: Future experimental options discussed in the March 21st Workshop organized by the Focus Group, and talks given to the Focus Group.

Type	channel	Background	Source	Production	Activity (Mci)		Proposal
ν_e	$\nu_e e \rightarrow \nu_e e$ Compton edge 5% E_{res} 15cm R_{res}	radioactivity (managable) Solar ν (irreducible) ν-Source (out ok but in ?)	^{51}Cr 0.75 MeV $t_{1/2}$=26d	n_{th} irradiation in Reactor	in	>3	Baksan LENS
					out	5-10	Borexino SNO+
			^{37}Ar 0.8 MeV $t_{1/2}$=35d	n_{fast} irradiation in Reactor (breeder)	in	>1	-
					out	5	Ricochet (NC)
$\bar{\nu}_e$	$\bar{\nu}_e p \rightarrow e^+ n$ E_{th}=1.8 MeV (e^+,n) Coincidence 5% E_{res} 15cm R_{res}	reactor ν & ν-Source → Background free!	^{144}Ce E<3MeV $t_{1/2}$=285d	spent nuclear fuel reprocessing	in	0.005-0.05	CeLAND Borexino
					out	0.5	Daya-Bay
			^{90}Sr ^{106}Rh		-	-	-
			^{42}Ar	?	-	-	-

Table 5: Proposed "long-lived" radioactive source experiments, where "in" and "out" refer to geometries where the source is within the detector, or outside of the detector.

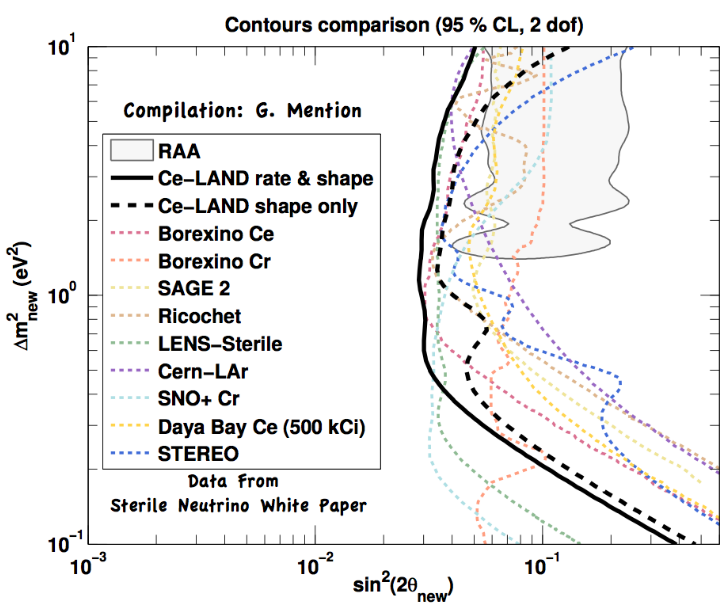

Figure 4: Anticipated sensitivities for proposed "long-lived" source experiments, compared to the region of sterile neutrino parameter space indicated by the reactor anomaly (light gray area).

Very short-lived radioisotopes can also be used if produced in situ by, for example, a low energy high power cyclotron. In one scenario, a 5 mA, 60 MeV proton beam might be used to produce neutrons via the reaction $^9Be(p,n)^9B$ followed by neutron capture on ^{11}B to form ^{12}B. The resulting ^{12}B has a 30 ms lifetime and β^- decays to ^{12}C with a 13 MeV endpoint, producing an intense flux of $\bar{\nu}_e$. One candidate detector under consideration is KamLAND which, with a source-detector distance of 5-20m, might provide impressive sensitivity to time dependent neutrino transitions corresponding to *L/E* = O (1) m/MeV.

6.2 Reactor Experiments

Reactors create a large variety of radioisotopes which then β-decay to produce $\bar{\nu}_e$ with energies in the range of 2-8 MeV. Although the absolute anti-neutrino flux from reactors is difficult to determine, two detectors at different baselines can mitigate the associated uncertainties. There are proposals to use smaller core reactors for short baseline oscillation searches because the large core of high power reactors constitutes a significant smearing in distance and hence *L/E*. As with source measurements, reactors experiments can only measure disappearance. Table 6 summarizes the near-term and presently proposed short-baseline reactor experiments, and Fig. 5 shows that, for Δm^2 less than a few eV^2, the anticipated sensitivity for one representative example covers the region of sterile neutrino parameter space indicated by the reactor anomaly.

6.3 Accelerator Driven Decay-at-Rest Sources

The LSND measurements used a stopped pion/muon source. A more definitive measurement might be made using two detectors at different distances, with larger detectors than LSND and/or a more intense pion/muon source. If the beam pulse is much shorter than the muon lifetime, the relatively prompt mono-energetic 30 MeV neutrinos from stopped pion decay can be separated from the neutrinos from muon decay, enabling the search for the appearance of a 30 MeV ν_e. In addition, the mono-energetic 30 MeV ν_μ will interact only via the weak neutral current, enabling a disappearance search. Candidate host laboratories for an intense, time-separated stopped pion decay source are SNS (1MW source, 500 ns pulse), or Fermilab in the Project X era.

Stopped kaon decays might also offer an avenue to search for sterile states. High-energy proton beams can produce high rates of stopped kaons. The stopped $K^+ \to \mu^+\nu_\mu$ decay, similar to the stopped pion decay, produces a mono-energetic, 236 MeV neutrino. In a similar way, it could be used to search for sterile neutrino oscillations via disappearance and appearance channels.

Proposal	Reactor	Fuel (#fissions)	Core Size (m)	<L> (m)	Depth (mwe)	Status	Comment
Nucifer Saclay	Osiris 70 MW	^{235}U ON-OFF cycle	<1	7	5	Data Taking	Non proliferation 1 m^3 Gd-LS Mostly Rate + Shape?
Stereo Genoble	ILL 50 MW	^{235}U ON-OFF cycle	<1	10	10	Proposal	2 m^3 Gd-LS Rate + Mostly shape
SCRAMM (Ca)	San-Onofre 3 GW PWR	$^{235,238}U$ $^{239,241}Pu$	3x3.8	24	30	Proposal	2 m^3 Gd-LS Mostly Rate + Shape
SCRAMM (Idaho)	ATR 150 MW	^{235}U ON-OFF cycle	<1	12	15	Proposal	2 m^3 Gd-LS Rate + Mostly shape
DANSS (Russia)	KNPP 3 GW PWR	$^{235,238}U$ $^{239,241}Pu$	few	14	70	Being Built	Segmented detector 1 m^3 Rate + Shape?
NIST (US)	NCNR 20 MW	^{235}U ON-OFF cycle	≈1	4-11	0	Proposal	Rate + Mostly shape

Table 6: Near-term and Proposed short-baseline reactor experiments.

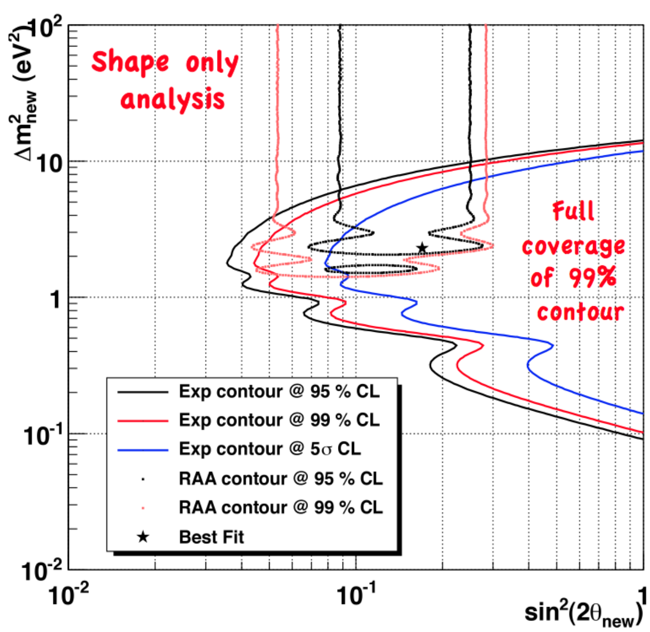

Figure 5: Anticipated sensitivity for one representative short-baseline reactor proposal (Stereo at ILL) compared to the region of sterile neutrino parameter space indicated by the reactor anomaly.

6.4 Accelerator Driven Decay-in-Flight Source

Conventional decay-in-flight beams produce neutrinos and/or antineutrinos from the decays of muons, pions, and kaons. In order to maximize intensity, horn focused wide-band beams, tuned for the desired neutrino spectrum, have been used. One can obtain ν_μ or $\bar{\nu}_\mu$ beams in this way, and depending on the desired spectrum, experiments can be located on-axis or off-axis. Detector options include mineral oil Cherenkov detectors, which are a proven technology, and liquid argon detectors, which are being developed for long-baseline, experiments, and have very fine granularity, electron-photon discrimination, and imaging capabilities. Examples of the latter are MicroBooNE, a proposed two-detector experiment LArLAr that would use the Booster neutrino beam, and a proposed experiment at CERN in which a new neutrino beam is built, driven by a 100 GeV primary beam from the SPS, and the ICARUS T600 detector is moved from Gran Sasso to CERN. It is anticipated that the CERN experiment would cover the LSND/MiniBooNE preferred sterile neutrino parameter space at greater than 99% C.L.

More ambitious decay-in-flight beams produced by muons stored in a racetrack-shaped ring have also been proposed. One option is the Neutrino Factory (NF), in which low energy pions decay to produce muons in an external decay channel. The muons are then captured into bunches and manipulated to reduce their phase-space so that the beam intensity increases. Finally, the muons are accelerated to the desired energy and injected into the storage ring. This produces a beam consisting of 50% ν_e ($\bar{\nu}_\mu$) and 50%, $\bar{\nu}_e$ (ν_μ) with well-known fluxes, and enables a search for $\nu_e \rightarrow \nu_\mu$ and $\bar{\nu}_e \rightarrow \bar{\nu}_\mu$ transitions, which has a distinct signature (wrong-sign muons) with a very low background. The beam intensity for the full NF greatly exceeds that required for the next generation short-baseline experiments, enabling a phased approach to be considered. Possible first stages include a pion/muon storage ring with no NF technology ("νSTORM"), which uses the wrong-sign muon signature proposed for the NF, and an "Entry Level NF" which enhances νSTORM with the addition of some NF technology to increase the intensity.

7 EVOLUTION OF ACCELERATOR FACILITIES

Three major laboratories maintain facilities for the production of high-energy protons and neutrinos: CERN, Fermilab, and J-PARC. Each of these laboratories is a potential host for future short-baseline experiments. The following describes the various accelerator complexes and neutrino beams that are operating or under consideration at these laboratories (Tables 7 and 8). Each laboratory has considered many options for the future evolution of their accelerator facilities. We restrict ourselves to operating facilities and those with plans far enough along to be described with reasonable confidence.

Table 7 summarizes present operations for each laboratory, and rough scenarios for future operations. In each of these scenarios there are multiple proton beams at various energies. The maximum expected power is listed for each beam. For many of these beams, however, other users are expected to significantly impact the beam available for a potential short-baseline neutrino program. Note also that in each case some portion of the lower energy beam must be used to produce the higher energy beams – this effect is not accounted for in the table. The presently planned allocation of protons for neutrino physics varies from laboratory to laboratory:

- At CERN, the CNGS neutrino beam only uses a small fraction of the SPS protons. Most of the SPS protons are used for filling the LHC and for North Area experiments.

- At Fermilab, the NuMI (and/or LBNE) beams are expected to take the vast majority of the Main Injector protons.

- At J-PARC, the T2K beam plans to operate on the MR about half time, but will be the sole user during that time.

Table 8 summarizes present neutrino beams and future neutrino beam configurations under consideration. Additional configurations are possible at each facility. Those that are not likely to be used for substantial beam production (e.g. special beams for understanding of systematic effects) are not listed.

7.1 Fermilab

Fermilab presently operates an accelerator complex consisting of a Linac, Booster synchrotron, and Main Injector synchrotron (MI) feeding two neutrino beams: the NuMI beam (MINOS, MINERvA, ArgoNeuT, and NOvA) and the Booster Neutrino Beam (MiniBooNE, SciBooNE, and MicroBooNE). Booster and NuMI beams can be operated simultaneously, which offers the possibility of having multiple detectors seeing multiple beams. This capability is unique to Fermilab, and might be exploited to combat systematic uncertainties associated with fluxes, cross-sections, and detector performance.

The two neutrino-beams at Fermilab are tuned for their various primary experiments. Each of them has some flexibility. The Booster Neutrino Beam can be operated with various horn currents of either sign. The NuMI beam can also manipulate its horn current, but has additional flexibility in the positioning of its targets and horn. This flexibility allows substantial tuning of the peak energy of the neutrino beam. Furthermore, the NuMI beam has experiments at various angles to its axis (e.g. NOvA), which therefore see different peak neutrino energies. Future neutrino beams at Fermilab have been proposed for various purposes. The most mature proposal is the LBNE beam and is included for analysis here.

The recent performance of the Fermilab complex is enumerated in Table 9. The number of protons delivered is tracked in four cases:

- the Booster for all users
- the Booster Neutrino Beam (MiniBooNE)
- the Main Injector for all users
- NuMI

Accelerator uptime is calculated from operational records for the accelerator complex; it does not account for downtime due to experimental facilities (including the neutrino beam). The fractional uptime as part of a year is shown. The number of protons for each beam is also re-interpreted as an average power during that uptime, and the average power over all the seconds of a year. An estimated "nominal" power of the Main Injector is included for each year (In 2008 slip-stacking was implemented, increasing the nominal power). Finally, the ratio average power over the year to the nominal power is calculated.

Facility – Scenario	Accelerator	Notional Beams
Fermilab – 2012	Main Injector (MI) Booster	350 kW @ 120 GeV 35 kW @ 8 GeV
Fermilab – ANU/PIP	Main Injector Booster	700 kW @ 120 GeV 80 kW @ 8 GeV
Fermilab – PrX Phase 1	Main Injector Booster Project X Linac	1200 kW @ 120 GeV 125 kW @ 8 GeV 1 MW @ 1 GeV
Fermilab – PrX Phase 2	Main Injector Booster Project X Linac Project X Linac	1200 kW @ 120 GeV 125 kW @ 8 GeV 2 MW @ 3 GeV 1 MW @ 1 GeV
Fermilab – PrX Phase 3	Main Injector Project X Linac Project X Linac Project X Linac	2.3 MW @ 120 GeV 300 kW @ 8 GeV 2 MW @ 3 GeV 1 MW @ 1 GeV
Fermilab – PrX Phase 4	Main Injector Project X Accumulator Rings Project X Linac Project X Linac	2.3 MW @ 120 GeV 4 MW @ 8 GeV 2 MW @ 3 GeV 1 MW @ 1 GeV
J-PARC – 2012	Main Ring (MR) Rapid Cycling Synchrotron (RCS)	150 kW @ 30 GeV 200 kW @ 3 GeV
J-PARC – RCS/MR Upgrades	Main Ring Rapid Cycling Synchrotron	750 kW @ 30 GeV 1 MW @ 3 GeV
J-PARC – Ultimate	Main Ring Rapid Cycling Synchrotron	1.7 MW @ 30 GeV 1+ MW @ 3 GeV
CERN – 2012	Super Proton Synchrotron (SPS) Proton Synchrotron (PS)	500 kW @ 400 GeV 60 kW @ 25 GeV
CERN – LIU Program	Super Proton Synchrotron Proton Synchrotron 2 (PS2)	750 kW @ 400 GeV 400 kW @ 50 GeV
CERN – LPSPL + HPPS	High-Power Proton Source (HPPS) Low-Power Superconducting Linac (LPSPL)	2 MW @ 50 GeV 190 kW @ 4 GeV
CERN – HPSPL	High-Power Superconducting Linac (HPSPL)	4 MW @ 5 GeV

Table 7: Present and future primary beams under discussion and/or consideration.

Neutrino Beam	Configurations	Status
Fermilab NuMI	Low Energy Low Energy Antineutrino Medium Energy Medium Energy Antineutrino Off Axis Off Axis Antineutrino	Operating
Fermilab Booster Neutrino Beam	Neutrino Antineutrino	Operating
Fermilab LBNE	Neutrino Antineutrino	Planning
J-PARC T2K	Neutrino	Operating
CERN CNGS	Neutrino	Operating
CERN Short Baseline	Neutrino Antineutrino	Planning
CERN SPL Neutrinos	Neutrino	Planning

Table 8: Present and future neutrino beam configurations under discussion and/or consideration.

	FY	2005	2006	2007	2008	2009	2010	2011	2012
	Uptime (hours)	5848	4532	5897	6514	5334	6825	6585	4007
	Fractional Accelerator Uptime	66.7%	51.7%	67.3%	74.3%	60.9%	77.9%	75.1%	45.7%
Booster	Protons Delivered (e20)	3.64	3.23	4.18	5.32	4.57	6.16	6.46	4.30
Booster Neutrino Beam	Protons Delivered (e20)	2.52	1.71	1.48	2.30	1.50	1.66	3.21	1.60
Main Injector	Protons Delivered (e20)	1.13	1.49	2.74	2.90	3.04	4.29	3.22	2.67
NuMI	Protons Delivered (e20)	0.68	1.02	1.90	1.98	2.17	3.23	2.22	2.56
Booster	Ave. Power during Uptime (kW)	22	25	25	29	31	32	35	38
Booster Neutrino Beam	Ave. Power during Uptime (kW)	15	13	9	13	10	9	17	14
Main Injector	Ave. Power during Uptime (kW)	104	176	249	239	305	337	262	357
NuMI	Ave. Power during Uptime (kW)	62	121	173	163	218	254	181	342
Booster	Ave. Power for the year (kW)	15	13	17	22	19	25	26	18
Booster Neutrino Beam	Ave. Power for the year (kW)	10	7	6	9	6	7	13	7
Main Injector	Ave. Power for the year (kW)	69	91	168	177	186	262	197	163
NuMI	Ave. Power for the year (kW)	42	62	116	121	133	198	136	157
MI Nominal Power	Power (kw)	250	250	250	350	350	350	350	350
	Fraction of nominal, per year	27.6%	36.4%	67.0%	50.7%	53.1%	74.9%	56.3%	46.6%

Table 9: Recent performance of the Fermilab accelerator complex.

Two projects are in progress to increase beam power available at 8 and 120 GeV: the Proton Improvement Plan (PIP) and the Accelerator and NuMI Upgrades (ANU) for NOvA. Beyond that Fermilab has a broad program of new accelerators and upgrades, called Project X, which has been divided into four phases. Each phase significantly increases the available beam at various energies including 1, 3, 8, and 120 GeV. Table 10 summarizes the expected availability of protons for the medium-term under the assumption that Project X starts construction in 2017.

	ANU												
	PIP												
					PrX								
	2013	**2014**	**2015**	**2016**	**2017**	**2018**	**2019**	**2020**	**2021**	**2022**	**2023**	**2024**	**2025**
8 GeV Power - Full (kW)	40	60	65	70	80	80	80	80	80	125	125	125	125
8 GeV Protons/yr - Full (e20)	5	8	9	10	12	12	12	12	12	19	19	19	19
8 GeV Power - Avail (kW)	15	15	20	25	35	35	35	35	35	45	45	45	45
8 GeV Protons/yr - Avail (e20)	2	2	3	4	6	6	6	6	6	9	9	9	9
120 GeV Power (kW)	400	700	700	700	700	700	700	700	700	1200	1200	1200	1200
120 GeV Protons/yr (e20)	3	6	6	6	6	6	6	6	6	10	10	10	10

Table 10: Expected profile of available beam power at Fermilab over the medium-term. The ANU and PIP projects are projected to occur at their present rate, and a 2017 construction start is indicated for Project X Phase 1.

Tables 7 and 10 show that the high energy proton beam power at Fermilab is competitive with the corresponding beam powers at CERN and J-PARC, and will remain competitive through the PIP and Project-X eras. Project-X Phase 1 will add a 1 MW beam at 1 GeV, enhancing the capabilities of the complex with a competitive beam in this energy range. However, the currently planned beam power at 8 GeV is not obviously competitive with multi-GeV beam powers at J-PARC and CERN. This potential weakness might become important if sterile neutrinos are discovered and the resulting program requires intense low energy pion decay-in-flight neutrino and anti-neutrino beams.

A study to understand better the potential for increasing the beam power at 8 GeV, and the resulting neutrino beam intensity, would be a worthwhile complement to PIP and Project-X studies.

This would help ensure that upgrades to the complex do not unnecessarily limit the laboratory's options in response to a discovery, and that options for increasing the intensity of future Booster Neutrino Beam experiments are well understood.

7.2 J-PARC

J-PARC presently operates an accelerator complex consisting of a Linac, a Rapid Cycling Synchrotron (RCS), and a 30 GeV Main Ring (MR). The MR is used to feed the Tokai to Kamioka (T2K) neutrino beam. J-PARC requires a series of upgrades to its Linac, RCS, and MR in order to reach its 750 KW design intensity. These upgrades are well into the planning phases. Additionally, there is a concept for the "ultimate" configuration of the J-PARC accelerators to produce a peak power of 1.7 MW.

T2K is the operating neutrino beam at J-PARC. No upgrades or alternative configurations are planned other than those necessary to accommodate higher beam power.

7.3 CERN

CERN presently operates an accelerator complex consisting of Linac 2, Proton Synchrotron Booster (PSB), Proton Synchrotron (PS), Super Proton Synchrotron (SPS), and Large Hadron Collider (LHC). The focus of CERN and its accelerators is providing beams to the LHC, however it has a substantial program of other users at various points in the chain. The CERN Neutrinos to Gran Sasso (CNGS) beam uses protons from the SPS to provide a neutrino beam to experiments in Italy (OPERA and ICARUS).

The mid-term evolution of the CERN accelerator complex consists of the LHC Intensity Upgrades (LIU). These upgrades are focused on improving the luminosity of the LHC, but will have some benefit for the fixed-target users. Additionally, CERN has other proposals for the long-term including a Low-Power Superconducting Proton Linac (LPSPL) combined with a High-Power Proton Synchrotron (HPPS), and a further possibility of a High-Power Superconducting Proton Linac (HPSPL).

In addition to the CNGS beam, CERN has been entertaining proposals to revitalize a short-baseline neutrino beam on site and various neutrino beams that could use the SPL as a source. While not enumerated in this section, there are of course options for entirely new beams at various points within the CERN complex.

8 RESPONSE TO THE CHARGE

1. *Evaluate to what extent the ongoing and planned neutrino experiments will be able to resolve the origin of each of the couple of sigma tensions with three-flavor mixing. Identify any additional measurements that might be needed, and options for making these measurements.*

The ongoing and presently approved experiments will not be able to definitively resolve all of the tensions with three-flavor mixing. This realization is motivating a vigorous program of proposed experiments at reactors and radioactive sources, and is also motivating a growing number of proposals for accelerator-based experiments. The reactor and source experiments will provide further tests of ν_e and anti-ν_e disappearance, but will not test the LSND/MiniBooNE anomaly. A new accelerator-based experiment is needed to definitively resolve the origin of this anomaly. Several options have been / are being proposed for review by the Fermilab PAC. Presently, these include BooNE, LArLAr, and νSTORM.

2. *Compare with competing facilities the future capabilities at Fermilab for supporting a short baseline neutrino program to definitively resolve the present anomalies, and suggest what the optimal short baseline neutrino program might be beyond the presently approved and running experiments.*

Fermilab (i) hosts the current short-baseline neutrino community in the U.S., and has arguably a more vigorous short-baseline neutrino program than any other laboratory in the World, and (ii) has two existing neutrino beams, offering the possibility of locating a detector to exploit both beams: one beam on-axis and the other off-axis. These assets are unique to Fermilab, and make the laboratory a natural host for new accelerator-base short-baseline experiments. The prospect of higher intensities in the Project-X era, is also attractive for a program that may need to expand further in the future, in the advent of a major discovery.

Since the Focus Group is not a program committee, it did not attempt to judge the cost/benefit or compare the sensitivities of the various proposals. However the group did consider the overall short-baseline strategy at Fermilab, which led to the recommendations below.

9 RECOMMENDATIONS

The emerging and/or persisting "anomalies" at accelerator experiments (LSND & MiniBooNE), reactor experiments, and radioactive source experiments, and the observation that all of these effects occur within overlapping ranges of *L/E*, has increased the interest in searching for sterile neutrinos. This increased interest is reflected in (i) the growing number of experimental proposals to search for light sterile neutrinos using radioactive sources, reactors, and accelerators, (ii) an increase in the number of workshops devoted to discussing the associated physics and future options for sterile neutrino searches, and (iii) an increase in the time devoted to sterile neutrino searches and physics at general neutrino meetings. The growing number of proposals and letters of interest makes urgent the consideration of the next steps to resolve the origin of the observed anomalies.

Although the tensions with three-flavor mixing may be due to statistical and/or systematic effects, there is the possibility that they are indicative of an emerging discovery. In view of this, a vigorous program of experiments is being proposed using reactors and radioactive sources, and it seems reasonable to assume that several of these proposed experiments will proceed. However, these experiments are disappearance experiments, and cannot definitively resolve the accelerator-based $\nu_\mu \rightarrow \nu_e$ anomalies.

A new Short-Baseline experiment at Fermilab is well motivated and is necessary to definitively resolve the LSND/MiniBooNE tensions with three-flavor mixing.

RECOMMENDATION 1:

The Focus Group recommends a Short-Baseline Plan for Fermilab with the following elements:

i) **MINOS+ to search for ν_μ disappearance at *L/E* values that overlap the coverage of the reactor experiments that report evidence for ν_e disappearance.**

ii) **MicroBooNE to clarify the nature of the MiniBooNE low energy excess.**

iii) **A new experiment to search for $\nu_\mu \rightarrow \nu_e$ and/or $\nu_e \rightarrow \nu_\mu$ transitions. The experiment should be capable of <u>both</u> excluding sterile neutrinos over the entire allowed LSND/MiniBooNE parameter space with a significance of at least 5σ, and of discovering sterile neutrinos if they exist within this region of parameter space, also with a significance of at least 5σ.**

It is also desirable that the new experiment be sensitive to ν_μ disappearance and/or ν_e disappearance to complement and/or go beyond the coverage of MINOS+.

It seems plausible that a new experiment could begin data taking before the end of the decade. The length of time needed for approval and construction depend upon the scope of the experiment and the availability of resources. However, an illustrative timescale is shown in Fig. R-1. If the reactor and/or source experiments make an early discovery that provides convincing evidence for sterile neutrinos, the new Fermilab short-baseline experiment, which presumably would be under construction, would provide Fermilab with a timely entry-point into a very exciting accelerator-based sort-baseline program. In this scenario, pursuing the new experiment at Fermilab as fast as is practical will add to its potential scientific impact in the face of almost certain competition.

RECOMMENDATION 2:

The Focus Group recommends that the new experiment (Rec. 1) be pursued as vigorously as is practical.

We note that LOIs have been written for several interesting options for a new short-baseline experiment at Fermilab.

RECOMMENDATION 3:

The Focus Group recommends there be a call for proposals for a new short-baseline experiment that can be evaluated by the PAC at one time, and that the evaluation be on a timescale that is as fast as is practical. The criteria for evaluating the proposals should include:

a. **The ability to discover, or exclude (at 5σ), sterile neutrinos over the entire parameter space indicated by the LSND and MiniBooNE results.**

b. **The expected statistical and systematic uncertainties, and the uncertainty on those uncertainties.**

c. **The possible upgrade path that might be followed IF there were a discovery.**

We note that some modest but timely support might be effective in enabling the various proposals to be more fully developed for consideration by the PAC.

RECOMMENDATION 4:

The Focus Group recommends that in the advent of a sterile neutrino discovery, either at Fermilab or elsewhere, the Fermilab short-baseline program be further expanded to include one or more additional experiments capable of exploring as many flavor transitions as practical over the appropriate *L/E* range. Indeed it seems likely, in this scenario, that the short-baseline program would become, for an extended period of time, a flagship of the domestic accelerator based program.

In addition to dedicated experiments to search for new physics at short-baselines, ancillary measurements to better understand neutrino cross-sections and neutrino beam fluxes will be an integral part of the program, and provide indispensible data for the interpretation of future long- and short-baseline experiments. The ability of these experiments to discover or exclude may ultimately be limited by cross-section and flux uncertainties. Recent Fermilab experiments at both the Booster and the Main Injector have added considerably to our knowledge of the important cross-sections. In the future, further MINERvA data taking, together with measurements from MicroBooNE, should continue to improve our knowledge of the relevant neutrino and antineutrino cross-sections.

The neutrino cross-section and flux knowledge needed for any given proposed experiment depend on the experimental details and the energy range being considered.

RECOMMENDATION 5:

The impact of cross-section and flux uncertainties on the sensitivity of any proposed new short-baseline experiment should be spelled out in the proposal, together with an assessment of the need for new cross-section and/or particle production measurements beyond those currently planned.

The currently planned beam power at 8 GeV is not obviously competitive with multi-GeV beam powers at J-PARC and CERN.

RECOMMENDATION 6:

A study to understand better the potential for increasing the beam power at 8 GeV, and the resulting neutrino beam intensity, should be undertaken.

This would help ensure that upgrades to the complex do not unnecessarily limit the laboratory's options in response to a discovery, and that options for increasing the intensity of future Booster Neutrino Beam experiments are well understood.

Finally, a summary of the plan corresponding to these recommendations is shown schematically in Fig. R-2.

Acknowledgements

The focus group is indebted to many members of the community that have developed and presented concepts for elements of the future short-baseline program. Credit for the ideas does not appear in this report, but can be found in the March 21st workshop presentations: https://indico.fnal.gov/conferenceDisplay.py?ovw=True&confId=5273. Fermilab is operated by Fermi Research Alliance, LLC under Contract No. De-AC02-07CH11359 with the United States Department of Energy.

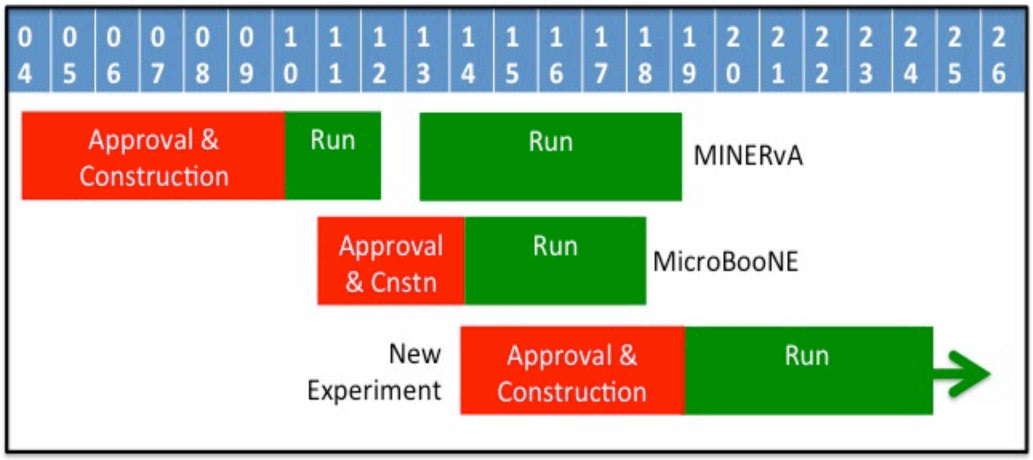

Figure R-1: Illustrative timeline for a new experiment beginning as soon as is practical.

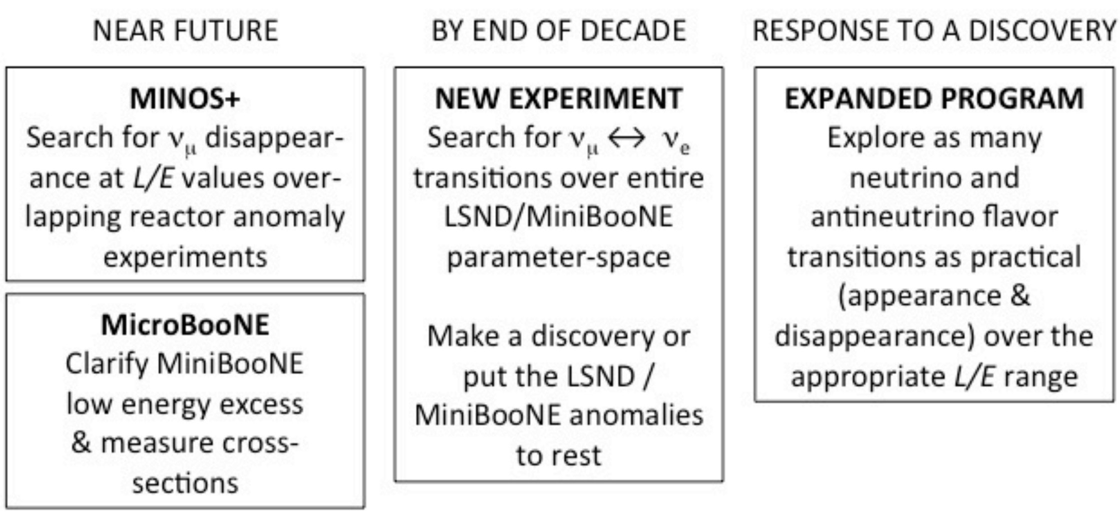

Figure R-2: Recommended Fermilab Sterile Neutrino Experiment "Plan".

APPENDIX 1: FOCUS GROUP MEMBERSHIP

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1) Chair
2) Tensions Group Facilitator
3) Options Group Facilitator
4) Cross-Section and Fluxes Group Facilitator
5) Facilities Group Facilitator

APPENDIX 2: FOCUS GROUP CHARGE

Several neutrino oscillation experiments have produced results that exhibit, at the level of a couple of standard deviations, a tension with the simple three-flavor mixing framework. These tensions might be purely statistical in origin, or might arise from one or more unidentified systematic effects, or from new physics. Together with the laboratory and the community, we would like to ask you to consider new generation detectors and/or new types of neutrino sources that would lead to a definitive resolution of the existing anomalies. With this in mind:

1. Evaluate to what extent the ongoing and planned neutrino experiments will be able to resolve the origin of each of the couple of sigma tensions with three-flavor mixing. Identify any additional measurements that might be needed, and options for making these measurements.

2. Compare with competing facilities the future capabilities at Fermilab for supporting a short baseline neutrino program to definitively resolve the present anomalies, and suggest what the optimal short baseline neutrino program might be beyond the presently approved and running experiments.

We would like the focus group to give an interim report by the end of March, 2012, to deliver the final report by May 31, 2012, and to give a presentation at the PAC meeting during the week of June 18th.

Young-Kee Kim

Deputy Director, Fermilab

cc: Pier Oddone
Greg Bock
Stuart Henderson
Vicky White
Jeff Appel

APPENDIX 3: SUB-GROUPS

1. **Tensions Group:** Summarize the tensions with three-flavor mixing, the expected impact of near-term ongoing/approved experiments, and the requirements for longer-term definitive experiments.

2. **Options Group:** Summarize options to be considered, including new detectors and/or new types of neutrino source.

3. **Cross-Sections and Fluxes Group:** Summarize near-term expectations for the uncertainties on relevant neutrino cross-sections and fluxes, and what is possible and desirable in the longer term.

4. **Facilities Group:** Summarize the parameters of the evolving Fermilab accelerators that are relevant for a short-baseline neutrino program, and compare with the corresponding parameters of the evolving facilities elsewhere.

TENSIONS GROUP

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