The Intermediate Neutrino Program

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Contents

1　Introduction

The US neutrino community gathered at the Workshop on the Intermediate Neutrino Program (WINP) at Brookhaven National Laboratory February 4–6, 2015 to explore opportunities in neutrino physics over the next five to ten years. Scientists from particle, astro-particle and nuclear physics [1] participated in the workshop. The US High Energy Physics community is now launched on the path defined by the 2014 P5 report. Two of the five P5 Science Drivers motivate neutrino physicists, *"Pursue the physics associated with neutrino mass"* and *"Explore the unknown: new particles, interactions, and physical principles"*.

Underlying these Drivers is the fact that in spite of tremendous recent progress in understanding neutrinos, we still lack a complete picture for the physical behavior and structure of the neutrino sector. There are many more questions yet to be answered: What is the neutrino mass ordering? Do neutrinos exhibit the same matter/antimatter symmetry seen in the charged leptons and quarks (Dirac fermions) or do they have a completely different structure (e.g., Majorana fermions)? Do they violate CP symmetry? What is the absolute mass scale of the neutrino sector and is it consistent with that implied from limits obtained by cosmological observation? Are experimental hints that there may be additional sterile flavors of neutrinos valid? How can we understand neutrino interactions with nuclei? Are there non-standard interactions of neutrinos representing beyond-the-Standard Model physics?

There are furthermore outstanding questions which can be answered using neutrinos as a probe, such as: What is the detailed mechanism behind stellar-collapse supernovae, and what physics can we learn from a supernova neutrino burst? Is the diffuse flux of neutrinos from past supernovae consistent with expectations from cosmology? Where do ultra high energy neutrinos come from? What fraction of the Earth's radiated heat comes from radioactivity? What fraction of the Sun's energy comes from the CNO cycle? What fission isotopes are the main producers of neutrinos and decay heat in a nuclear reactor core?

In accordance with one specific P5 recommendation, a large international collaboration (Experimental program at the Long-Baseline Neutrino Facility, ELBNF) has been formed to perform a long-baseline neutrino oscillation experiment with an underground liquid argon time projection chamber and a new neutrino beam from Fermilab. The main physics goals of ELBNF are to address some of the outstanding neutrino questions, by measuring the value of the CP-violating parameter δ and providing a definitive determination of the mass hierarchy, as well as to search for baryon number violation and record a burst of core-collapse supernova neutrinos. The community is also engaged in development of a short-baseline neutrino (SBN) program hosted at Fermilab, as a part of the P5 recommendataion for a short baseline neutrino portfolio, to operate coherently with the long-baseline program in order to address some of the short-baseline neutrino anomalies and support R&D towards ELBNF.

The Fermilab long-baseline effort is exciting and compelling, but is a long-term effort. Physics results and technical development in the short term (this decade) are essential for health of the field, for motivating young scientists and for sustaining innovation. The long-baseline oscillation program addresses some of the most critical questions in particle physics — yet other physics questions associated with neutrinos, including the ones listed above, deserve attention as well. Some of these are best addressed with smaller, lower-cost, dedicated experiments which can be completed on a shorter time scale than ELBNF. In addition, some issues will need large, advanced-technology detectors which require significant R&D for their realization.

The P5 report states: *Some of the biggest scientific questions driving the field can only be addressed by large and mid-scale experiments. However, small-scale experiments can also address many of the questions related to the Drivers. These experiments combine timely physics with opportunities for a broad exposure to new experimental techniques, provide leadership roles for young scientists, and allow for partnerships among universities and national laboratories. In our budget exercises, we main- tained a small projects portfolio to preserve budgetary space for a number of these important small projects,*

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[1] The nuclear physics community is currently in the midst of a Long Range Planning process that includes neutrino physics.

whose costs are typically less than $20M. These projects individually are not large enough to come under direct P5 review. Small investments in large, multi-disciplinary projects, as well as early R&D for some project concepts, were also accounted for here.
Recommendation 4: Maintain a program of projects of all scales, from the largest international projects to mid- and small-scale projects.

WINP explored opportunities for the broad US neutrino community to pursue physics in the next five to ten years, including projects of all scales. In addition to small- and mid-scale project ideas, WINP considered (consistent with the P5 recommendation) contributions to large offshore and multi-disciplinary projects, and to R&D efforts aimed towards future large experimental concepts. Some of these ideas and efforts are synergistic with the ELBNF and SBN efforts; others are complementary. Theory efforts related to the proposed long- and short-term experimental programs were also discussed. WINP also covered activities such as searches for neutrinoless double beta decay and direct mass measurements that are part of the neutrino physics program in nuclear physics.

The workshop was organized into two sets of parallel working group sessions, divided by physics topics and technology. Physics working groups covered topics on Sterile Neutrino, Neutrino Mixing, Neutrino Interactions, Neutrino Properties and Astrophysical Neutrinos. Technology sessions were organized into Theory, Short-Baseline Accelerator Neutrinos, Reactor Neutrinos, Detector R&D and Source, Cyclotron and Meson Decay at Rest sessions. Each working group formulated a set of bullet points with key findings and recommendations, which will be summarized in this report.

In addition to members of the particle and nuclear physics communities, representatives from the agencies participated in the workshop.

A major area of discussion centered around a possible Department of Energy Office of High Energy Physics Funding Opportunity Announcement (FOA) relevant to neutrino physics over a five-year timescale. Discussion sessions included community suggestions on physics topics and parameters for such a FOA. The general outcome of this discussion was that the community believes that a broader rather than a narrower scientific scope is important for any such FOA. There was no clear consensus on the appropriate fraction of available funds to be allocated to R&D efforts, but R&D was felt to be important. Potential for publishable results — either physics, or key technical results that advance the field — within five years should be the most important criterion. There was also community support to enable proposals for theoretical effort. These can be highly cost-effective and may strongly enhance the success of experimental efforts. The community felt that a suite of new experiments should be initiated, consistent with the P5 recommendation, to increase the breadth of the intermediate program beyond SBN at FNAL. A general sense emerged that some part of this new program should include sterile neutrino searches complementary to SBN and that part of this program should include some of the other exciting new initiatives discussed.

Although much discussion focused on the potential HEP FOA, the broader neutrino community was actively engaged at the workshop, and it was clear that there are additional opportunities for activities on an intermediate time scale. For example, another area of discussion was the importance of determining the nature of the neutrino. Whether neutrinos are Majorana or Dirac is of fundamental importance to their mass generation mechanism and to leptogenesis; the search for neutrinoless double beta decay offers the most promising (and possibly only plausible) avenue for addressing this question. The community recognizes the importance of the Nuclear Science Advisory Committee Neutrinoless Double Beta Decay subcommittee for providing guidance on a strategy for implementation of the next generation neutrinoless double beta decay experiment. In addition, many other intermediate activities — including R&D, theory, experiments and contributions to a variety of international efforts — are supported by the National Science Foundation and the DOE Office of Nuclear Physics as well as the Office of High Energy Physics.

2 Physics Working Groups

In this section we provide the summary reports of the physics-related working groups. These working groups convened in the morning of February 5, 2015 to discuss the outstanding physics questions in neutrino physics, with emphasis on those that can be addressed within the next decade.

- Sterile Neutrinos

- Three Neutrino Mixing

- Neutrino Interactions

- Neutrino Properties

- Astrophysical Neutrinos

2.1   Sterile Neutrinos

Sterile neutrinos appear in nearly every possible mechanism to explain neutrino mass. Dark matter and dark energy provide possible evidence for physics beyond the Standard Model in astrophysics, but neutrino mass has been the only such evidence so far found in particle physics. This should make the quest for understanding the origin of neutrino mass one of the priorities of the field.

Apart from these theoretical considerations, there have been persistent anomalies, observed in electron neutrino appearance and electron neutrino disappearance (For the disappearance channel neutrino and antineutrino oscillation probabilities are equal assuming CPT invariance and therefore we make no distinction in the remainder of the document), which in combination can be interpreted as evidence for one or several sterile neutrinos at around a mass of 1 eV and with oscillation amplitudes as large as 5–10%. At the same time, the lack of observations of muon neutrino disappearance at the relevant L/E values creates a significant tension in global fits. Currently, no phenomenological models are known that provide a better fit to the global data than sterile neutrinos. It therefore seems justified to use sterile neutrino oscillations as a phenomenological proxy for considering the required experimental capabilities to resolve these anomalies. In the event that the existence of sterile neutrinos is not the source of these anomalies, experiments optimized to eV-scale oscillations can be expected to also have good sensitivity to probe other new physics scenarios.

During the Snowmass process, P5 deliberations and WINP discussions, many different experimental approaches to this problem have been proposed and some have been studied in quite some detail and some have reached the prototype stage. Sterile neutrino searches build on detection techniques developed over the last several years, allowing for efficient experiment deployment at modest cost in some cases. Among the many proposed experimental approaches, electron neutrino disappearance searches using radioactive sources and reactors and some electron neutrino appearance searches seem to fit well within the scope of an intermediate neutrino program and would complement the Fermilab short-baseline program. Thus, a modest investment into sterile neutrino searches has the potential to discover a fundamental particle not predicted in the Standard Model for the first time since the Standard Model was formulated. This would be a paradigm-shifting discovery opening up vistas on an entirely new continent of possibilities. The U.S. community is well poised to play a leadership role and to have a vibrant program in this field.

In the somewhat longer term, and in particular in anticipation of a potential discovery of sterile neutrinos, directed R&D towards novel detector technologies and neutrino sources also would fit the boundary conditions of an intermediate neutrino program.

The working group's consensus can be summarized in the following five recommendations:

1. Sterile neutrinos are well motivated in many extensions of the Standard Model. Persistent experimental anomalies have focused attention on the eV mass scale. This makes sterile neutrinos the subject of low-risk but potentially high-reward experiments. Therefore, the P5 Planning Report recommends a targeted set of short-term, small-scale experiments.

2. Direct tests of existing anomalies should seek to demonstrate the sterile neutrino's oscillatory nature via signatures in energy and/or baseline.

3. Experiments designed to test both the ν_μ to ν_e appearance and ν_e disappearance channels are needed. We must ensure that any pion decay beam program has optimized ν_μ disappearance sensitivity.

4. Below the $5M level, individual experiments can have an impact on oscillation physics results within the WINP time constraints. In the $5–10M range, several proposed efforts have the potential to provide extensive coverage of the suggested oscillation parameter space.

5. Short-term investment in detector and source R&D towards future sterile oscillation experiments could reduce risk, lead to long-term cost savings, and provide the foundation for precision measurements in the case of observation of sterile neutrino oscillations.

2.2 Three Neutrino Mixing

Three neutrino mixing has been well established by a variety of experiments yielding consistent results. Besides the overall neutrino mass scale, there are three parameters that are still unknown in this framework and which can be better addressed in neutrino oscillation experiments: the neutrino mass ordering, δ_{CP}, and the octant of θ_{23}. The determination of these unknowns is of key importance to understanding the mechanism responsible for neutrino mass and potentially the generation of the matter-antimatter asymmetry in the early universe. The suite of presently running experiments are either directly exploring the three unknowns, or are producing results that will contribute to these measurements by reducing systematic and theoretical uncertainties (neutrino interaction measurements for example), or by precisely measuring related oscillation parameters (θ_{13}, θ_{23}, $|\Delta m^2_{atm}|$). Proposed and running experiments can potentially measure the ordering and θ_{23} octant in the next decade. The measurement of δ_{CP} is likely to take longer and require a dedicated large-scale experiment. If discrepancies are found in the measurement of one or more of these fundamental parameters across different experiments, it could point to new physics.

Recent results from the Daya Bay Reactor Neutrino Experiment [1] include the most precise measurement of $\sin^2 2\theta_{13}$ to date and a measurement of $|\Delta m^2_{atm}|$ that is comparable in precision and consistent with the long-baseline measurements. By Daya Bay's expected end date in 2017, it will provide the most precise measurement of $\sin^2 2\theta_{13}$ for many years to come. The Double Chooz experiment has recently installed their near detector, which will greatly increase the precision of their $\sin^2 2\theta_{13}$ measurements [2]. Double Chooz has the unique ability to take reactor-off data due to having only two reactor cores, allowing a strong constraint on the background in their θ_{13} analysis.

The combined data from the MINOS long-baseline experiment using the low-energy NuMI beam and atmospheric neutrino data in the MINOS far detector provides the most precise measurement of the atmospheric mass splitting [3]. MINOS+ is currently running in the medium-energy NuMI beam. Including these data in the fit will further improve the precision. Furthermore, the high statistics in the energy region just above the oscillation maximum puts MINOS+ in a unique position to test the validity of the three neutrino mixing model. T2K can also measure the atmospheric parameters and has made the most precise measurement of $\sin^2 \theta_{23}$. T2K also made the first observation of electron neutrino appearance. Assuming the value of θ_{13} from reactor data, T2K can exclude some values of δ_{CP} at the 90% confidence level [4]. The NOvA experiment at Fermilab has only just started running, but has the potential to determine the octant or the mass ordering within some range of the parameters in particular in combination with data from both T2K and MINOS+.

Super-Kamiokande continues to use atmospheric neutrino data to address the three main questions in three neutrino mixing and has recently included combined fits with T2K data [5]. A proposed upgrade for Super-Kamiokande in the intermediate program would involve adding gadolinium to the water to identify electron antineutrinos via the inverse beta decay interaction [6] enabling detection of diffuse supernova neutrinos. IceCube has recently presented results on the atmospheric mixing parameters that are consistent with and comparable in precision with results from Super-Kamiokande [7].

It is important to realize that precision measurements of oscillation parameters made by currently running experiments can have a significant effect on future projects — either in achievable precision, detector or beam design or in the running conditions (for example, neutrino beam vs antineutrino beam).

Besides these oscillation experiments directly addressing the determination of neutrino parameters, experiments collecting neutrino interaction data are also of great importance for constraining the models that are used in oscillation experiments for true-to-visible energy conversions, predictions of signal and background rates, etc. MINERvA is a dedicated neutrino interaction experiment that provides constraints for oscillation experiments directly and for neutrino event generators used in neutrino simulations. The MINERvA collaboration is currently finishing the analysis of their low-energy NuMI data (for example, [8]) while taking data in the NuMI medium-energy beam. A potential upgrade to the MINERvA detector is being proposed for the intermediate program. CAPTAIN, a liquid argon TPC [9] (LArTPC), would be combined with the MINERvA detector to measure neutrino-argon interactions in an energy range relevant for oscillation physics in ELBNF.

The US-NA61 program is a funded proposal to collaborate with the NA61/SHINE experiment at CERN [10] to make hadron production measurements important for the US neutrino program. They will expose targets and replicas of targets used at Fermilab to the NA61 hadron beam. Measurements of pion (and other hadron) spectra in p+C interactions can be used to tune models of primary interactions in the target and reduce uncertainties on the initial flux in oscillation experiments.

The NuPRISM collaboration is proposing an experimental method to remove neutrino interaction uncertainties from oscillation experiments using water Cherenkov detectors [11]. NuPRISM would measure neutrino interactions over a continuous range of off-axis angles and use these measurements to provide a direct measurement of the far detector lepton kinematics for any given set of oscillation parameters. With this, they can mostly remove neutrino interaction modeling uncertainties from oscillation measurements. This project is being proposed for the intermediate program.

There is also a group of longer term planned experiments designed to measure the last unknown elements of the three neutrino mixing model. These include JUNO, Hyper-K, PINGU, Theia, Daedalus, and ELBNF. Of these experiments, JUNO is the only one currently under construction. R&D for these large projects will be an important part of the intermediate neutrino program.

Within this context, the most relevant issues for these experiments to seek funding in this intermediate time scale are:

- Discovery potential and/or improved physics reach over other experiments
- Leverage existing resources
- Visible and significant US participation
- Low technical risk/familiar technology
- Potential for each to result in several graduate student theses
- US contribution of approximately $1M each

Of the experiments discussed in the three neutrino mixing working group, there are only a few proposals that will seek funding for the intermediate program. The above requirements are well fulfilled by these proposals, including proposed experiments measuring cross sections such as NuPrism and CAPTAIN-MINERvA, as well as upgrades to existing detectors like gadolinium in Super-Kamiokande. In addition, R&D for future projects described above is relevant, in particular for those which can lead to clearly definable US roles in international collaborations.

2.3 Neutrino Interactions

Significant investment is being made using accelerator-based sources of neutrinos to critically test the current 3-neutrino mixing picture and determine whether or not neutrinos violate CP. The detectors associated with this program use heavy nuclei to achieve the required event rates and modeling the interaction of neutrinos with these heavy nuclei is required. Now that neutrino oscillation experiments are evolving from the discovery to the precision stage, understanding the challenging role of the nucleus in neutrino interactions has become an imperative. It is needed to sort signal from background and to identify and minimize systematic uncertainties in neutrino oscillation investigations. It has therefore become essential to establish a more robust program of characterizing neutrino-nucleus interactions and promptly integrating these results into event generators. This difficult task requires the cooperative effort of theory and experiment from both nuclear and high-energy physics.

Nuclear theorists are providing far more realistic nuclear models than the relativistic Fermi gas, which has been the standard in event generators, however, many aspects of the theory are still not at the required level. Event generators have begun the process of including these improved although still incomplete advances, but manpower problems are a hindrance. Thus, agreement of generator predictions with data still remains a challenge and there is real concern with the accuracy of neutrino energy estimations [12, 13, 14]. This increased uncertainty in assigning the incident neutrino energy will become a serious issue for oscillation measurements in the future as statistics increase and the need for greater precision is required [15]. Furthermore, the HEP oscillation program requires current neutrino nucleus theoretical developments to be extended to higher-A such as Ar, to more relativistic energies and momenta and to include the yield of resonance production cross sections above the delta. Significantly, this important work by nuclear theorists has to be packaged in a form that can be swiftly incorporated into neutrino event generators. Although it is not yet clear how to do this, extensive collaboration between nuclear theorists, builders of event generators and neutrino experimentalists will be required. To achieve this, communication between the NP and HEP communities should be improved so that new theoretical advances can be more readily adopted.

In addition, the theory discussed above only describes inclusive cross sections. Calculating the wide variety of exclusive final states exceeds any current capability. Dealing with final state interactions (FSI) will require extensive recourse to phenomenology. Significantly more complete higher energy neutrino cross section data will be needed, especially for argon targets such as the proposed CAPTAIN-MINERvA collaboration. Additional input will likely come from electron scattering carried out at kinematics similar to those encountered in neutrino experiments. The electron beam at Jefferson Laboratory is ideal and there is a recent JLAB proposal [16] to carry out (e,e′p) measurements on ^{40}Ar. The event generators must then incorporate these data into appropriate models for existing and planned experiments.

It is critical to benchmark generators against both accelerator-based neutrino-nucleus interaction measurements and electron-nucleus interaction measurements. The current experimental neutrino interaction program continues to provide important data and should be supported to its conclusion. To further refine the nuclear model in event generators, future neutrino interaction measurements that span a range of neutrino and antineutrino beam energies as well as target materials will be needed to bring the current knowledge to the level required to reach the goals of the long baseline oscillation program. The progress in developing a broad international GENIE collaboration with a core group at FNAL is encouraging.

Understanding the subtleties of the nuclear environment and their effect on neutrino experiments needs the input of nuclear physics theorists specializing in this topic. It is important to create an established procedure that allows nuclear theorists to join neutrino generator experts and neutrino experimentalists in working toward this goal. NuSTEC (Neutrino Scattering Theory Experiment Collaboration, http://nustec2014.phys.vt.edu) has been established directly to provide this environment. A current example of such a project is the work on Green's Function Monte Carlo techniques by a collaboration of Argonne, Jefferson Lab, and Los Alamos nuclear theorists with Fermilab neutrino experimentalists. A white paper (Lovato, A. et. al. "Quantum Monte Carlo Methods for Neutrino-nucleus Interactions", FERMILAB-FN-0997-ND-T, JLAB-THY-15-2012, LA-UR-15-21054) from a collaboration of NP theo-

rists and HEP neutrino experimentalists has been submitted to DOE-HEP and DOE-NP and is now being expanded to a full joint HEP-NP proposal to be submitted to the DOE.

A summary of this Neutrino Interactions working group's discussions in the form of a prioritized list follows:

1. The Neutrino-Nucleus Interaction is the least understood component of a detectors response to neutrinos.

2. Improvements of nuclear models by nuclear theorists are essential. This can most efficiently be accomplished with additional financial support of NP theorists working in this area to provide a more robust model to meet the requirements of the oscillation program. Rapidly incorporating these improvements in event generators is equally important and requires a collaborative effort of the HEP and NP communities.

3. The current experimental neutrino interaction program (MINERvA, NOvA-ND, MicroBooNE, T2K Near Detector) continues to provide important data and should be supported to its conclusion. This includes efforts to improve the precision with which the neutrino flux is known.

4. The critical role of neutrino nucleus event generators needs to be emphasized and more community resources devoted to keeping them widely available, accurate, transparent, and current.

5. Future neutrino interaction measurements such as the Fermilab short-baseline program (SBN) and the CAPTAIN-MINERvA experiment are needed to extend the current program of GeV-scale neutrino interactions. The feasibility of a high-statistics deuterium experiment should be considered. Current and future long-and-short-baseline neutrino oscillation programs should evaluate and articulate what additional neutrino nucleus interaction data is required to meet their ambitious goals and support experiments that provide this data.

6. Measurements and theoretical work are also needed to characterize neutrino interactions in the low energy regime (≤ 100 MeV). This regime is especially relevant for core-collapse supernova neutrinos, and understanding is essential for development of future underground detectors. This is also an area of collaboration where NP would bring in critical expertise.

2.4   Neutrino Properties

Neutrinos are the most enigmatic particles in the Standard Model. Identifying their properties may go beyond merely filling out the few missing entries in the Particle Data Book. The absolute value of the neutrino mass has cosmological implications. The magnetic moment of the neutrino is a sensitive probe of TeV-scale physics beyond the Standard Model. And identifying the quantum field nature of the neutrino, i.e. whether it is a Dirac or Majorana fermion, may determine if Lepton Number is a fundamental symmetry of Nature, and shed light on the long-standing puzzle of the abundance of matter in the visible Universe.

2.4.1   Absolute neutrino mass

Absolute values of the neutrino masses are among the last unknown parameters of the new (ν) Standard Model. The combined results of absolute neutrino mass searches, neutrinoless double beta decay searches, and cosmology provide an extraordinary constraint on the neutrino mass spectrum and models of the neutrino mass [17]. Several experiments have been discussed at the workshop: KATRIN, Project-8 and electron capture in ^{163}Ho. In the US, direct measurements of the neutrino mass are generally supported by DOE-NP and NSF.

KATRIN represents the state of the art of the presently available technology. It will reach its ultimate sensitivity (0.2 eV at 90% C.L., 0.35 eV for a 5σ discovery) by the beginning of the next decade. This sensitivity is comparable to precision available from cosmological and neutrinoless double-beta decay constraints expected on a similar timescale, which may provide even deeper understanding of neutrinos. KATRIN is currently in commissioning, and is expected to start operations with the tritium source in 2016.

Techniques that may ultimately exceed KATRIN precision are in development. Project-8 is a novel idea of measuring the momentum spectrum near the tritium end-point using microwave cyclotron radiation spectroscopy [18]. The proof-of-principle demonstration with a ^{83m}Kr source has recently been reported [19] in a small-volume trap. First operations with a tritium source are planned and sensitivity similar to KATRIN is possible by the end of the decade. Ultimately, a large $O(5$ m$^3)$ volume experiment with an atomic tritium source may start approaching the sensitivity to the neutrino mass below the inverted hierarchy region. On the timescale of next decade, such measurement would be complementary to direct measurements of the hierarchy at ELBNF and cosmological constraints on the neutrino mass of similar sensitivity.

Experiments looking to measure the end-point of the electron capture spectrum, e.g. in ^{163}Ho using bolometric micro-calorimeters are in development (ECHO and HOLMES in Europe, NuMECS in the US). These experiments employ large arrays of low-mass bolometers with a ^{163}Ho source embedded in the absorber. Novel readout techniques are being explored to enable multiplexed readout of the a large number of channels; these efforts can benefit from synergy with the large-scale CMB arrays (supported by DOE-HEP through the CMB-S4 experiments). Large-scale production of ^{163}Ho sources at reactor facilities needs further development and would benefit from the domestic isotope production program, e.g. within the scope of DOE-NP Isotope Program (Isotope Development & Production for Research and Applications or IDPRA). Micro-calorimeter experiments aim to scale to 10k–100k channels in about a decade, promising to reach sensitivity to the neutrino mass below 0.1 eV.

2.4.2   Coherent elastic neutrino-nucleus scattering (CEvNS) and neutrino magnetic moment

Coherent Elastic Neutrino-Nucleus Scattering (CEvNS) is a yet-unobserved process that is cleanly predicted by the Standard Model. The US community is leading the effort towards the first observation of this process, which may be possible with relatively modest investments in the next few years. Coherent scattering experiments are also sensitive to an anomalous magnetic moment of the neutrino. Detection

requires low energy thresholds and high-intensity neutrino sources, thus there is complementarity with several other programs (neutrino scattering, dark matter detection). Once observed, CEvNS could help constrain models with non-standard neutrino interactions, have sensitivity to nuclear weak charge, and would offer complementary constraints on the sterile neutrino sector.

A variety of source/detector configurations are being considered in the search for CEvNS. Measurements with low-energy sources would rely on the low-threshold detectors developed for dark matter searches at reactors (e.g. RICOCHET) or with high-intensity radioactive sources (e.g. ^{51}Cr deployed in LZ). Measurements at higher energies at accelerators (e.g. COHERENT at SNS and CENNS at Fermilab) would use more conventional technologies. Searches for CEvNS match well to the parameters of the program discussed at this workshop: they can result in the first observation and sensitive limits on the neutrino magnetic moment within 5–10 year timeframe, and with modest investments (<$10M).

The RICOCHET experiment leverages significant R&D and engineering on low energy threshold detectors for SuperCDMS. It would deploy a tower of six SuperCDMS detectors near a research reactor. With energy thresholds as low as 100 eV$_{nr}$ already achieved at SuperCDMS, several thousand events per month could be observed, depending on the reactor and distance to the core. A critical issue is understanding the in-situ backgrounds and could benefit from synergy with short-baseline searches for sterile neutrinos at reactors. Proponents expect first deployment in the next few years and results on a 5–10 year timescale. RICOCHET Phase-II [20] would operate underground with an intense electron capture source (e.g. ^{51}Cr), which requires development of even lower threshold detectors and large active mass.

Another possibility for deployment of an intense electron capture source such as ^{51}Cr is the veto region of the LZ dark matter detector [21]. With a 5 MCi source 1–2m from the active volume and the low LZ energy threshold, detection of CEvNS is possible with high significance. The experiment could also place limits on the neutrino magnetic moment in the range of $(3–4)\times10^{-12}\mu_B$, better than any terrestrial limit to date and comparable in sensitivity to astrophysical constraints. This effort is complementary with the sterile neutrino program and could benefit from an enhanced US isotope production and isotope enrichment program.

Experiments with intense accelerator-based sources, such as the COHERENT [22] experiment with a DAR source at SNS and CENNS [23] at the BNB facility at Fermilab offers perhaps the most expeditious way of detecting CEvNS. COHERENT would deploy multiple neutrino detectors in the vicinity of an intense neutrino source from the SNS. Ge detectors (a test module from the MAJORANA DEMONSTRATOR neutrinoless double-beta decay experiment), CsI crystals, as well as a 100 kg LXe 2-phase TPC are being considered. The collaboration has identified several possible deployment sites at SNS and has measured in-situ backgrounds. The Phase-I program is ongoing, with the first neutrino scattering results expected this year, and a possibility to discover CEvNS within three years. The collaboration is receiving generous support from ORNL and commitment from other national labs, as well as in-kind contributions from international partners.

2.4.3 Majorana/Dirac nature of neutrinos (Neutrinoless Double-Beta Decay)

Searches for Neutrinoless Double-Beta Decay ($0\nu\beta\beta$) aim to discover whether Lepton Number is a fundamental symmetry of nature or is violated, and to determine the Dirac or Majorana nature of neutrinos. The current generation of experiments will search for $0\nu\beta\beta$ with a sensitivity to the effective Majorana mass of order 100 meV [24]. The next generation of experiments will aim for an order of magnitude improvement in sensitivity to the effective Majorana mass. With "tonne-scale" isotopic mass and ultra-low background next-generation experiments can discover $0\nu\beta\beta$ if it proceeds via light Majorana neutrino exchange and if the lightest neutrino mass is above ~ 50 meV, or if the spectrum of neutrino masses is "inverted" [17]. Even if neither of these two conditions is respected in Nature, a discovery is possible if other mechanisms contribute to the decay. While the potential for discovery of the Lepton Number Violation in $0\nu\beta\beta$ is independent of the neutrino mass hierarchy, sensitivity to the smallest possible masses consistent with the inverted hierarchy is a milestone goal: with cosmological and terrestrial constraints on

the neutrino masses and the mass hierarchy expected next decade, the next-generation $0\nu\beta\beta$ experiments can be definitive.

Planning for the next-generation tonne-scale $0\nu\beta\beta$ experiment now is timely, and would help maintain US leadership in the race for a Nobel-caliber discovery. The US community is gearing towards selecting the leading candidates for one or more next-generation experiments, under the stewardship of DOE-NP. A targeted program of R&D activities towards mature concepts of next-generation experiments is one of the priorities identified by the recently convened NSAC-NLDBD committee.

Experimental efforts with a significant US participation were presented at this workshop: CUORE and CUPID, Majorana Demonstrator and 1 tonne Ge effort, EXO-200 and nEXO, NEXT, KamLAND-Zen and NuDot, SNO+ and Theia, SuperNEMO. The talks focused on the current status and on the R&D needed for the next-generation, tonne-scale experiments.

The R&D effort towards definition of the next-generation $0\nu\beta\beta$ experiment is proceeding at a vigorous pace. There is possible synergy with the R&D activities in other areas of neutrino science as well as broader detector technology efforts within DOE-NP and DOE-HEP. For instance, there is a general need for reliable designs of high-voltage distribution systems in noble-gas liquid and gas TPCs, which could benefit from cooperation between $0\nu\beta\beta$, dark matter and ELBNF experiments. Development of large liquid scintillator and WbLS detectors, and in particular techniques for isotope loading, improvements in light yield and transparency are common to KamLAND-Zen, SNO+, Theia, NuDot and others. Low-background techniques, including low-mass, low-noise custom electronics which could be deployed near sensitive detector volumes could benefit both $0\nu\beta\beta$ and dark matter efforts. Those efforts also benefit from ongoing cooperation in improving radio-assay capabilities and sensitivities. Novel sensor technology development cuts across disciplines, from neutrino science to large-scale CMB experiments, to $0\nu\beta\beta$ and dark matter experiments. Finally, availability of a large quantity of isotopically enrichment material will be critical for most future $0\nu\beta\beta$ experiments. Further development of domestic isotopic enrichment capabilities, building on the existing DOE-NP Isotope Program (IDPRA), would be beneficial to the broad US-based neutrino physics program.

2.5 Astrophysical Neutrinos

2.5.1 Low Energy Astrophysical Neutrinos

Low energy astrophysical neutrinos (typically below about 100 MeV) result from stars either: a) going about their usual business of nuclear fusion and emitting a steady stream of solar neutrinos, or b) living fast, dying young, and leaving a good-looking corpse, in the process producing a spectacular burst of supernova neutrinos. These astrophysical neutrinos are important physics messengers, carrying information on extreme environments and complex processes that would be otherwise entirely inaccessible, namely what is going on in the center of stars as they live and die. They have a storied history in particle physics: the first observations of solar neutrinos (in the 1960's) and supernova neutrinos (in the 1980's) resulted in a shared 2002 Nobel Prize in physics. Famously, the long-standing "Solar Neutrino Problem" turned out to be the first indication of physics beyond the standard model, a glimpse at the effect of neutrino oscillations.

What remains to be done on the intermediate time (and money) scale? For solar neutrinos the main job for the next few years will be to measure neutrinos produced by the CNO cycle and to explore the MSW resonance in the sun. For supernova neutrinos from an explosion in our galaxy, the most important thing is to be ready to collect as much of this precious data as possible when it arrives, preferably with complementary technologies to study the various neutrino flavors and features of the event, particularly the initial neutronization burst and the final collapse to a black hole. While waiting for the next galactic burst to arrive the diffuse flux of supernova neutrinos from ancient supernova explosions can also be collected, provided a detector is big enough and sensitive enough.

In the coming five years it is expected that an upgraded Super-Kamiokande enhanced with gadolinium, Borexino, and SNO+ will be the major solar neutrino experiments in operation; over the same period Super-Kamiokande with gadolinium, SNO+, and WATCHMAN will be the main "new" projects with significant supernova neutrino sensitivity. At the same time, CAPTAIN will be providing insight into the supernova neutrino capabilities of liquid argon detectors like ELBNF, while R&D on water-based liquid scintillator should prove a good investment for longer-term projects like THEIA, which would be capable of studying both solar and supernova neutrinos.

2.5.2 High Energy Astrophysical Neutrinos

High energy astrophysical neutrinos ($\sim$100 MeV–10^{20} eV) can be separated into two categories:

1. The "atmospheric neutrinos", which are neutrinos produced terrestrially in the earth's atmosphere as a result of high energy cosmic rays interacting with the atmosphere, and have been detected with energies of $\sim$100 MeV to over 100 TeV.

2. The "high energy astrophysical neutrinos", which are neutrinos produced and originating from extra terrestrial sources, for example from high energy astrophysical processes in distant astrophysical objects, high energy cosmic ray interactions in the universe or neutrino production by exotic matter and particle physics processes such as dark matter annihilation. The neutrino energies of these processes are observable above backgrounds at energies of $\sim$10 TeV and above, and have recently been observed for the first time at energies up to 2 PeV. This newly discovered neutrino source holds promise for determining the origin of the highest energy cosmic rays that has remained a mystery for over 100 years and to open a new energy window for observing astrophysical objects and the physical processes responsible for producing the highest energy particles in the universe.

During this workshop the working group identified three areas appropriate for possible funding by a program aimed at the "intermediate" time and money scale. These include:

1. Funding for a cosmogenic (GZK) neutrino detector using radio detection techniques. These projects include the ARA and ARRIANA programs both located in Antarctica.

2. Funding for R&D on photodetector, instrumentation and deployment systems development for large channel count and physically large volume detectors. Possible projects include IceCube-Gen2 at South Pole and for related technologies in other science categories such as PINGU, CHIPS, Theia and others.

3. Funding for theoretical work on neutrino production at high energies in atmospheric neutrinos, and in particular the uncertain flux of the so called "prompt" neutrinos from charm production processes in cosmic ray interactions with the atmosphere.

3 Technology Working Groups

In this section we provide the summary reports of the technology-related working groups which convened in afternoon parallel sessions on Febrary 5, 2015. These working groups covered methods, including theory and R&D, for addressing the physics goals discussed in the physics working groups.

- Short-Baseline Accelerator Neutrinos

- Reactor Neutrinos

- Source, Cyclotron and Meson Decay at Rest Neutrinos

- Neutrino Detector R&D

- Neutrino Theory

3.1 Short-Baseline Accelerator Neutrinos

Accelerator decay-in-flight (DIF) neutrino beams provide an excellent opportunity for near-term, cost-effective neutrino experiments pursuing a variety of exciting physics and detector development goals. The US is home to two existing neutrino beams, both located at Fermilab. The Booster neutrino beam (BNB) has the significant advantage of being at shallow depth and parallel to the ground, enabling the deployment of multiple detectors at different baselines for relatively modest construction costs. Improvements to the performance of the BNB are currently under consideration and would significantly strengthen all experiments that utilize this beam. Preliminary studies indicate that a significant flux increase is feasible by fitting a second horn in the existing beam facility, although a detailed schedule and cost estimate needs to be prepared as recently requested by the Fermilab Physics Advisory Committee (PAC). New experiments on the Main Injector neutrino beam (NuMI) are also possible, but are limited by existing space in the underground near detector cavern.

A major element of the intermediate neutrino program will be the Short-Baseline Neutrino (SBN) program of three liquid argon detectors along the BNB [25]. The SBN program can resolve a class of experimental anomalies in neutrino physics and perform the most sensitive searches to date for sterile neutrinos at the eV mass-scale through appearance and disappearance oscillation channels in an accelerator DIF neutrino beam. Additional physics includes the study of neutrino-argon cross sections with millions of interactions using the neutrino fluxes of the BNB (on-axis) and NuMI (off-axis) beams. This program brings together an international team of scientists and engineers to advance LArTPC technology for neutrino physics while utilizing its capabilities to explore one of the exciting open questions in neutrino physics today. The SBN program was awarded Stage-1 approval at Fermilab in February 2015. Preparation of the three detectors is proceeding rapidly in order to match a tight time schedule that anticipates first data in 2018. MicroBooNE is now installed on the BNB and ready for commissioning, ICARUS is being refurbished at CERN in preparation for operations at shallow depth, and detailed designs are being developed for the near detector, LAr1-ND.

The Accelerator Neutrino Neutron Interaction Experiment (ANNIE) [26] is another proposal to utilize the on-axis flux of the Booster neutrino beam. ANNIE is a gadolinium doped water detector instrumented with advanced photodetectors that will measure neutron production in GeV-scale neutrino interactions, something presently not well understood and that represents a limiting factor in proton decay and supernova neutrino measurements in large water detectors. ANNIE also presents an opportunity to demonstrate new Large Area Picosecond Photodetector (LAPPD) technology [27], now being commercialized through the DOE STTR program, in the context of a neutrino detector. ANNIE was awarded Stage-1 approval following the January meeting of the Fermilab PAC.

The CAPTAIN detector [9], a 5 ton LArTPC being built at Los Alamos National Laboratory, anticipates running in both the BNB and NuMI neutrino beams. By positioning the detector far off-axis at the BNB, CAPTAIN can study low energy neutrino interactions (10s of MeV) to better understand neutrino interactions in the energy range of supernova neutrinos that may be observed in future large LAr detectors. The CAPTAIN-MINERvA experiment involves positioning the CAPTAIN detector in front of the existing MINERvA detector in the NuMI near detector hall to make precision measurements of neutrino-argon cross sections in the multi-GeV energy range.

The NuPRISM detector [11] represents a novel approach to substantially reducing the impact of neutrino cross section model uncertainties in long-baseline oscillation experiments, and has been proposed as part of the near detector complex at J-PARC in Japan. By sampling the neutrino beam at angles from 1–4 degrees off-axis, representing different ranges of neutrino energy, NuPRISM can map out the relationship between neutrino energy and the observed lepton kinematics. NuPRISM, in combination with the existing T2K near detector, also has sensitivity to sterile neutrino oscillations by sampling the beam at the same L but different E_ν ranges. Finally, NuPRISM can construct mono-energetic beams to make unique neutrino cross section measurements, such as the first ever neutral current cross sections as a function of neutrino energy, and the separation of traditional CCQE events from interactions involving several nucleons.

Accelerator neutrino beam facilities and precision neutrino detectors present another exciting opportunity for the interim physics program. By running in a 'beam-dump' mode (steering the proton beam off the target and into the beamline absorber), searches can be performed for dark sector particle production with reduced neutrino backgrounds. The MiniBooNE experiment has recently collected data in this mode and is currently analyzing the results [28, 29]. The LAr detectors of the SBN program present an opportunity to perform similar searches in the future with enhanced sensitivity.

The need to understand the physics being pursued with these short-baseline accelerator beam experiments (anomalies, sterile neutrinos, neutron production, neutrino-nucleus cross sections) and the importance of developing detector technologies for the future neutrino program motivate an aggressive time scale for each of these experiments, making them ideal for an interim neutrino program on the road to the next-generation US long-baseline experiment.

3.2 Reactor Neutrinos

Reactor neutrinos have played a central role in the history and our understanding of neutrinos. From the first experimental observation of the neutrino by Reines and Cowan at the Savannah reactor in the 1950's [30] to the demonstration of neutrino oscillations with KamLAND [31] and the recent precision measurement of the neutrino mixing angle θ_{13} [32, 33], reactor neutrinos have provided us with a unique tool for discovery for over five decades. Reactor experiments have advanced our understanding of the 3-neutrino framework and enabled the most precise measurement of neutrino mixing.

Emission of electron antineutrinos from reactors provides a flavor-pure source of antineutrinos with energies up to ~8 MeV. Reactor neutrinos are studied at distances as close as several meters from the reactor core and up to hundreds of kilometers. The abundant flux of antineutrinos from a nuclear reactor allows experiments to probe for new physics such as sterile neutrinos and neutrino magnetic moments, observe coherent neutrino scattering, and determine the neutrino mass hierarchy. The detection and study of reactor antineutrinos allows the monitoring and study of the power and fuel composition of reactors and finds application in non-proliferation and safeguards.

3.2.1 Physics Reach and Discovery Potential

Over the next decade neutrino experiments will make precision tests of 3-neutrino oscillations, aim to understand anomalous signatures in the current suite of neutrino data, determine the mass hierarchy and search for new CP violation. Reactor experiments will play a unique role in this program and provide discovery potential of new physics at modest costs. The observation of sterile neutrinos or other new physics would be a paradigm shift and set the course of particle physics for years to come. The resolution of the neutrino mass hierarchy is fundamental to understanding the neutrino mass spectrum and will provide important input to the search for neutrinoless double decay. Precision measurements of neutrino mixing parameters and knowledge of the mass hierarchy will help maximize the physics reach of long-baseline experiments and are fundamental to any extensions to the Standard Model.

Measurements of the reactor neutrino flux and spectrum compared to recent models of reactor antineutrino production have revealed discrepancies in both the total measured reactor antineutrino flux as well as the energy spectrum of neutrinos. The observed flux is found to be ~5–6% low [34, 35] while the recent θ_{13} experiments have revealed a distortion in the 4–6 MeV region of the spectrum. The observed discrepancies may point to new physics such as eV-scale sterile neutrinos. The observed spectral features already indicate that nuclear models in the predictions of the antineutrino flux from reactors are incomplete. The latter is also supported by recent measurements of the antineutrino spectrum from selected nuclei [36, 37, 38]. A well-controlled measurement of the antineutrino flux and spectrum at short-baselines can directly address these questions simultaneously with a unique measurement of the ^{235}U antineutrino spectrum at a compact research reactor. A search for antineutrino oscillations over meter-long baselines probes the hypothesis of sterile neutrinos in the appropriate mass region and has discovery potential to new physics. A measurement of the flux and spectrum can inform our understanding of antineutrino emission from reactors. Over distances of some fifty kilometers the observed oscillated energy spectrum provides a unique method for the determination of the mass hierarchy along with precision measurements of neutrino mixing parameters.

3.2.2 Reactors and Experimental Facilities

The US has several reactor facilities that are well-suited for short-baseline experiments at distances of $O(10\,\text{m})$. The NIST, HFIR, and ATR reactors in the US operate at 20–250 MW with highly enriched ^{235}U, provide easy access and technical support for a world-leading short-baseline reactor neutrino experiment. Other compact, high-power sources for antineutrinos such as a naval reactor are being explored. Through international collaboration the US neutrino physics community also has an exciting opportunity to participate in a medium baseline experiment overseas near the Taishang and Yangjiang reactors in China.

3.2.3 Small-Scale & Short-Baseline: Sterile Neutrinos and Reactor Spectrum

A domestic short-baseline experiment designed to resolve the reactor neutrino anomaly through oscillation and spectral measurements has the potential to discover new physics in the next 3–5 years at modest costs of $3–4M. Proposed short-baseline reactor disappearance experiments such as NuLAT [39] and PROSPECT [40] are complementary to the FNAL short-baseline program focusing on appearance measurements, and will answer both the question of short-baseline oscillation and our understanding of the reactor antineutrino spectrum. The proposed projects have deployed test detectors at NIST and HFIR, are ready to proceed with full design and construction, and provide an opportunity for world-leading, high-impact science at modest costs. In a technically limited schedule, data taking can begin in 2016 with first physics results in 2017. Given US experience and available reactor facilities, the US is in an excellent position to host and lead a short-baseline reactor experiment. The experiments offer opportunities for international collaboration with Canada, China, and Europe. Several other efforts reactor experiments worldwide are at various stages of development. This includes SOLID, STEREO, DANSS, and Neutrino-4. Experiments proposed in the US aim to optimize physics sensitivity to both the reactor spectrum and neutrino oscillations, proceed in a phased approach, and provide comprehensive systematic control through novel scintillator and detector technologies, movable detectors, and extensive background control. Detectors proposed in the US offer the highest energy resolution of ~4.5% which provides unmatched capability in the measurement of the reactor spectrum. This comprehensive and phased approach will maximize the discovery potential, limit technical risk, and provide flexibility to respond to future discoveries. Timely execution is critical to guarantee the highest impact and facilitate European participation in a US experiment.

3.2.4 Mid-Scale & Medium-Baseline: Mass Hierarchy and Oscillation Parameters

Medium-baseline experiments aim to determine the neutrino mass hierarchy without matter effect and precisely measure θ_{12}, Δm_{21}^2, and Δm_{32}^2. over the next 7–10 years [41]. A US contribution can make a critical impact to one of these overseas experiments. The JUNO experiment in China and RENO-50 in Korea are designed to determine the neutrino mass hierarchy and precisely measure oscillation parameters. In particular, the JUNO experiment, hosted by China and with substantial European contributions, offers strong leveraging of the successful US-China collaboration. The US is well-positioned to make an important contribution to JUNO. Near-term R&D of a few $M can help define US scope focused on the calibration system with an eventual US JUNO contribution of order $20M over 5–8 years. A reactor experiment at medium baselines represents an excellent opportunity to continue the long-standing US-China collaboration and ensures US leadership in the determination of the mass hierarchy.

3.2.5 Synergies

Measurements of reactor neutrinos are also relevant to nuclear physics and applied reactor safeguards. The proposed experiments will continue the long-standing US expertise in this area. Short-baseline experiments provide opportunities for detector R&D into technologies such as novel neutron-sensitive scintillators and highly segmented detectors. This work leverages R&D and LDRD support from several sources including DOE HEP, NP, and NSF as well as NIST. Large reactor antineutrino detectors offer synergistic opportunities for geo-neutrino physics and astrophysics. Many of the theoretical and experimental challenges are common across these fields and reactor neutrino measurements have the potential to uniquely inform these communities.

3.3 Source, Cyclotron and Meson Decay at Rest Neutrinos

Isotope and meson decay-at-rest (DAR) processes can be used to provide very high-intensity sources of neutrinos and antineutrinos with energies spanning a few MeV to a few hundred MeV. This energy range is ideal for a number of physics measurements including sterile neutrino searches with baselines of 10–100 meters, searches for and the possible discovery of coherent elastic neutrino-nucleus scattering (CEvNS), and neutrino cross section measurements relevant for astrophysical processes such as supernova explosions. There are trade-offs in cost, schedule, and sensitivity so a diverse program of possible technologies and setups can cover the wide range of possible physics opportunities. High-activity radioactive sources can be produced at reasonable cost and, when coupled with large, low-background detectors, can have good sensitivity to electron neutrino and antineutrino oscillations to sterile neutrinos. Very high rates of radioactive isotopes that produce higher energy neutrinos can be continuously produced by high-intensity cyclotrons and lead to conclusive studies of sterile neutrino oscillations. Spallation neutron sources such as the SNS and the JPARC-MLF facilities are copious sources of neutrinos from meson DAR in the spallation production dumps. Small, fairly low-cost detectors with good low energy capabilities can be used at these facilities to search for the elusive CEvNS process. These facilities could also host very sensitive sterile neutrino oscillation experiments using large detectors in the 50–1000 ton scale. The sections below outline the features of experiments using these sources including information on cost, timescale, and physics coverage.

3.3.1 Small-scale Experiments

Radioactive Source Experiments

Radioactive source experiments could be a cost effective way to investigate electron antineutrino disappearance in the region of the reactor anomaly. The SOX program [42] will use high-intensity radioactive sources of neutrinos or antineutrinos to investigate disappearance oscillations. The initial data run would use sources placed below the Borexino detector. Details of the cerium source production are described in [43]. This phase is expected to have physics results within 5 years (cerium run will be finished by the end of 2017, followed by a chromium run that should be finished by mid 2018). The physics results are expected to probe at 95% C.L. the entire Reactor Antineutrino Anomaly region. This phase will also provide important R&D for future upgrades relevant to SOX and the US ^{51}Cr program on LZ, SNO+, RICOCHET and possibly others. This initial phase would have a cost in the $2–3M range and fit into the proposed FOA category. Future upgrades could include higher intensity sources and deployment of the sources within the detector to get enhanced oscillation parameter space coverage.

JPARC-MLF Pion/Kaon Decay-at-Rest Experiment

JPARC-E56 [44] will directly probe the LSND anomaly with $\bar{\nu}_e$ appearance using a 50 ton Gd-doped liquid scintillator detectors at the JPARC-MLF (1 MW) 3 GeV spallation neutron facility. First data is expected in the next 2–3 years. The experiment will provide competitive (95% C.L. coverage), but not definitive, sensitivity to the LSND allowed region. The project is of modest scale with Japanese costs at the $5M level, but has the potential for upgrades and additional detector modules. The main US contribution to JPARC-E56 will be the dilute Gd-loaded liquid scintillator, which represents an important technological R&D step in producing doped scintillator for detecting both Cherenkov and scintillation signals. This effort will fit well into the FOA scope with an estimated cost of $1.5M.

The JPARC-MLF beam also uniquely allows the possibility to study kaon decay-at-rest (KDAR) [45, 46] muon neutrinos and related physics for the first time with an expected sample of over 10^5 muon neutrino charged current events. The KDAR muon neutrinos are mono-energetic with an energy of 236 MeV. As the only relevant known-energy muon neutrino above the charged current threshold, this unique neutrino can be used for studying short baseline oscillations indicative of a sterile flavor, neutrino cross sections relevant for future CP violation searches, and nuclear physics with a known-energy, weak-interaction-only probe.

Coherent Elastic Neutrino-Nucleus Scattering Experiments

Coherent Elastic Neutrino-Nucleus Scattering (CEvNS) is an unambiguous prediction of the Standard Model. Recent advances in detector design now put this so-far elusive prize within reach. Such a measurement will open the door to a host of new ways to better understand neutrino properties, and to search for new physics. CEvNS represents an eventually dominant background for dark matter detection, and its measurement will demonstrate dark matter detector response. As a neutral current process, it will be a new tool for sterile neutrino oscillation experiments.

The COHERENT experiment [22] will search for CEvNS at the SNS with three detector targets (CsI, Xe, Ge). The 1.4 MW SNS has a flux of 3.3×10^7 ν cm^{-2} s^{-1} at 20 m with a clean pion DAR spectrum. A neutron measurement campaign has identified several suitable deployment sites within 30 m of the source. Phase 1 of the experiment is likely to produce initial results within the year, and would have a cost of \$2–3M, fitting well into the proposed FOA category.

The CENNS experiment [23] will search for CEvNS at the BNB with a redeployment of the MINI-CLEAN detector to Fermilab. The 32 kW BNB has a flux of 5×10^5 ν cm^{-2} s^{-1} at 20 m. Measurements indicate that backgrounds from neutrons are manageable with sufficient shielding, in a green field site. The first results are expected after 2018, and are coupled to the physics program of MINICLEAN. The expected cost is \$2M, which fits well into the proposed FOA category.

3.3.2 Mid-scale Experiments

The IsoDAR Isotope Decay-at-Rest Experiment

The IsoDAR experiment [47, 48] will make a highly definitive investigation of electron antineutrino disappearance in the reactor anomaly region and make precision electroweak measurements searching for neutrino non-standard interactions. The experiment uses a very high intensity ^{8}Li antineutrino source placed near a large scintillator detector such as KamLAND or JUNO. IsoDAR can also be coupled with WATCHMAN and provide an important component of the WATCHMAN physics program. The cost of IsoDAR is estimated to be \$30M so it is a mid-scale project. At this point, the development of the IsoDAR cyclotron and neutrino source needs engineering R&D support at about the \$1M level to complete prototypes and prepare a Conceptual Design Report to be submitted to the agencies.

The OscSNS Pion Decay-at-Rest Experiment

OscSNS [49] has the capability to make a definitive search for electron antineutrino appearance using a pion DAR beam with much lower uncertainties than LSND. The cost is at the \$12M scale for civil construction and \$8M for a new 800 ton liquid scintillator detector with a start date 3 years after initiation. With the high neutrino rate at SNS, the experiment can cover the full LSND signal region in 2 years with some capability to see oscillatory behavior for $\Delta m^2 > 1$ eV^2. The successful support by DOE NP for infrastructure development at the SNS related to the fundamental physics neutron beamline and support facility can serve as a model for future infrastructure development related to OscSNS and other neutrino efforts supported by DOE HEP.

3.3.3 Cross Section Measurements using DAR Neutrino Sources

DAR neutrino sources can be used to measure a number of important neutrino interaction cross sections. Neutrino-nucleus cross-section measurements on various targets are inputs to supernova modeling and for understanding supernova detectors. Specifically, the CENNS, CAPTAIN-BNB [9], JPARC-MLF, and COHERENT (Ge, CsI, Xe) at SNS experiments will address many of these cross-section measurements. For example, ongoing measurements of the neutrino-induced neutron background for COHERENT play an important role in r-process nucleosynthesis, as well as in the HALO SNe experiment [50]. To make these measurements one needs to understand the flux spectrum, the detector characteristics and the backgrounds. Neutron backgrounds are the most important and need to be addressed by location or shielding.

3.4 Neutrino Detector R&D

3.4.1 Water and Liquid Scintillator

Development of new scintillator materials and doping agents has proven critical to the advancement of neutrino detector design. Further development of these materials is a critical step for future experiments; supporting this effort should be a high priority in the intermediate program. This program includes target development and characterization, including: light yield and timing measurements at low and high energy, energy nonlinearity, and attenuation measurements.

The newly-developed water based liquid scintillator (WbLS) could enable a massive detector with a broad physics program at relatively low cost. A particularly nice feature is the potential to separate fast, directional Cherenkov light from the slower yet far more abundant isotropic scintillation light. Should this be achieved, this would enable astonishing advances in signal identification and background rejection capabilities via particle identification, resulting in vast improvements in physics reach. This potential capability should be explored via both optimization of the WbLS target — by modifying the LS fraction and thus relative magnitudes of the Cherenkov and scintillation components, by use of various additives to delay the scintillation light, or wavelength shifters to minimize absorption/reemission of Cherenkov light — and alternate photon detection methods. The ability to reconstruct event energy and direction in (Wb)LS needs to be demonstrated both theoretically (in simulation) and in practice (in small scale experiments).

Large water Cherenkov and (water-based) scintillator detectors require very high purity target liquids. Purification techniques for water are well understood in industry and need no R&D, but further development is required for (Wb)LS purification. At the same time, a program to determine compatibility of construction materials with (Wb)LS must exist for future detectors.

Isotope loading in traditional liquid scintillator, Gadolinium doping in water detectors, and the potential to load metallic isotopes in WbLS broaden the potential physics program and significantly enhance the sensitivity of future experiments. Techniques to load isotope while maintaining the optical purity of the target should continue to be developed.

A driving cost and critical performance factor in large-scale water or scintillator detectors is the photomultiplier tubes. R&D to produce low cost, large area, ultra-fast photon detectors is important for the neutrino community. Correspondingly fast, high precision readout will be critical to take advantage of developments in photon detector technology.

Water-based detectors (including WbLS) have the advantage of a low cost detector medium allowing very large-scale experiments. Future experiments will be limited by the cost and excavation techniques for the cavern needed to house the experiments. R&D to find lower-cost construction methods, including PMT deployment and readout techniques, can facilitate next-generation neutrino detectors.

Several projects are underway that can address these topics. These range from bench-top scale development and characterization of newly-developed WbLS and LS for next-generation large-scale detectors, primarily at BNL but also at U. Chicago, U. Penn, LBNL, Iowa State, and MIT, to full-scale projects such as EGADS (Gd loading), ANNIE (fast timing), WATCHMAN phase II (WbLS deployment, fast timing), SNO+ (Te loading), and CHIPS (large-scale construction). This collaborative effort is supported by DOE-HEP, DOE-NP, NSF and LDRD. Ultimately such projects will inform the design of a massive future detector such as the proposed THEIA experiment.

3.4.2 Liquid Argon

Several ongoing and proposed experimental efforts will provide R&D that will substantially improve understanding of LArTPC performance or potentially expand the capabilities of the ELBNF experiment. Test beam measurements are especially important as they provide critical data for improving the detector

model and understanding of systematic uncertainties. The majority of these experiments will use the test beam facilities at FNAL or CERN or the neutrino beams at FNAL. Support for these efforts can be a combination of R&D funding at FNAL, SBN or ELBNF project funding, funding from an intermediate neutrino program or other agency or laboratory funding. Careful evaluation and prioritization of these experiments by the FNAL PAC including an evaluation of impact of R&D by these experiments is expected, and should provide important guidance to the selection process. However, the substantially larger funding available to the FNAL projects should also be taken into account. Only one experiment that will provide critical R&D needed for the ELBNF program is outside the FNAL program: the neutron cross section measurements proposed by the CAPTAIN experiment are necessary to understand the detector response and energy resolution.

The following factors should be taken into account when evaluating the impact different experiments could have on the long range program:

- A comprehensive test beam program must be performed to characterize present and future LArT-PCs. This is necessary to calibrate the detector response of existing and future LAr detectors and to verify systematic error estimates. This program should include electromagnetic and hadronic showers measurements, neutron cross section measurements, and energy deposition measurements with different charged particle beams at appropriate energies. Experiments which could contribute to this are LArIAT, CAPTAIN, and the CERN neutrino platform experiments.

- R&D on the generation and breakdown of high voltage will reduce the risk to future LAr detectors and could lead to more monolithic and lower cost detector designs based on longer drifts. The causes of HV breakdown in LAr are not well understood. If the process for HV discharge in LAr is better understood then detectors could be designed for higher voltages (if the electron lifetime is sufficiently large). This could lead to larger, cheaper detectors and could enable dual-phase style detectors. R&D on LAr feedthroughs above 100 kV is needed as manufacture of LAr feedthrus for voltages above 100 kV has only been achieved successfully by a small number of groups.

- The processes for contamination generation and transport inside large liquid argon detectors are not well understood. Better modeling of the sources and migration of contaminants in large cryogenics systems will aid future detector design.

- R&D that improves the understanding of the generation and propagation of both light and charge in large LArTPCs will improve the detector model for ELBNF.

- Present photon detector designs capture a very small fraction of the scintillation light generated in large LArTPCs. Detectors with better light collection efficiency should be developed.

- Development of cold electronics for LArTPCs is critical. Advanced designs for cold preamps and ADCs exist but a control chip is only in early stages of development. Development of electronics to read out large arrays of SiPMs is necessary.

3.5 Neutrino Theory

During the workshop on Intermediate Neutrino Program held at Brookhaven National Laboratory in February 2015, the neutrino theory community organized a vibrant session which highlighted the physics goals that can be achieved in the near term future and the role that theory plays in achieving these goals. This section summarizes the consensus that emerged from these discussions. We include specific recommendations which should help the funding agencies in considering support for the neutrino program through investments in theory; including, but not limited to any potential FOA in this area.

Theory plays an essential role in making advances in neutrino physics. Theory input is necessary in almost all facets of experimental neutrino physics. Theoretical tools are required to interpret cross section measurements, to formulate oscillation paradigm with 3 or more neutrinos, to seek the underlying neutrino mass generation mechanism, to connect experiments with cosmology and astrophysics, and to infer the fundamental properties of neutrinos.

A relatively small investment in neutrino theory in the intermediate time scale will provide huge dividends that would enrich the community as a whole. It would result in timely development of theoretical models for neutrino-nucleus cross sections, phenomenological studies on the impact of cross section uncertainties, theoretical cross checks of the 3 neutrino oscillation paradigm with tools such as global fits, model-building advances to understand large mixings and possible light sterile neutrinos, and potentially unravel the underlying symmetry that plays a role in neutrino mass generation. *The neutrino theory community thus recommends support for neutrino theory and that the language of any potential FOA for the intermediate neutrino program be broad enough to allow potential theory proposals.*

The theory perspective on the physics goals that can be achieved in the near term future are highlighted below.

(A) Fundamental neutrino properties:

(1) *Dirac versus Majorana nature of the neutrino:* Improved searches for neutrinoless double beta decay are the best bet to address this fundamental question. If neutrinos obey an inverted mass spectrum observable signals may be within reach in such experiments in the near future. Searches for neutrinoless double beta decay should continue without waiting for the mass hierarchy measurement, as there may be surprises here, such as lepton number violation mediated by TeV scale particles. **(2)** *Direct neutrino mass measurement*: Determining the absolute neutrino mass scale in tritium beta decay experiments would provide deep insight into the origin of neutrino masses. **(3)** *Sensitivity to mass hierarchy and possibly CP violation:* Any progress towards measuring the neutrino mass hierarchy before ELBNF would be highly desirable. In particular, knowing the hierarchy is crucial for the possibility of obtaining a hint for the value of the leptonic CP violating phase prior to ELBNF. **(4)** *Consistency checks of the three neutrino oscillation paradigm:* This requires a variety experimental information including: (a) Improved knowledge of neutrino oscillation parameters from solar, atmospheric, accelerator and reactor neutrino experiments; and (b) Essential information on neutrino interaction rates from experiments, aided by theory.

(B) Neutrino interactions:

Knowing the interaction rates is crucial for addressing many of the important questions in neutrino physics. For example, Over much of the available parameter space, discovery of leptonic CP violation at ELBNF will require, as-yet unachieved, percent-level control over ν_e appearance signals. A dominant source of uncertainty on this signal is due to the modeling of neutrino interactions with the target nucleus in the near and far detectors. Relating the fundamental quark-level interactions of the neutrino to the complete nuclear response is a difficult field theory problem, involving both particle and nuclear physics. Unlike in the collider physics community, where there is vibrant interactions between researchers in the domains of (i) detector modeling and event simulation at the hadron level, (ii) perturbative QCD analysis at the parton level and (iii) model building and theoretical interpretation, presently the situation is very different in the analysis of signals at accelerator based neutrino experiments. The analogs of (i) and (ii)

above are both relegated to the nuclear physics community. This has two unfortunate outcomes. First, many tools in the particle theorists toolkit are not brought to bear on these problems. Second, there is an institutional barrier to communication between those researchers studying neutrino models, and those involved in understanding the experimental analysis of signals and backgrounds. Collaborative efforts involving HEP theorists, nuclear theorists and neutrino experimenters can uplift this area of research to a level comparable to the one seen in collider physics today.

(C) Short baseline anomalies and sterile neutrinos:

   (1) *Understanding anomalies seen in short baseline experiments*: Unambiguous resolution in terms of oscillations would require seeing L/E dependence in new/upgraded experiments. **(2)** *Existence of sterile neutrino*: Discovery of new sterile states in neutrino oscillation experiments attempting to resolve short baseline anomalies will be foundational. **(3)** *Nonstandard neutrino interactions*: If discovered, these effects would invalidate the three neutrino oscillation paradigm, and hint at new physics beyond neutrino masses.

(D) Neutrinos in astrophysics and cosmology:

   (1) *Supernova neutrinos*: Anticipating neutrinos from supernova explosions in the near term future, we feel that investment in understanding the complex dynamics of collective neutrino oscillation is necessary, and that this should happen now, as it could influence detector design decisions in the next several years. **(2)** *High energy astrophysical neutrinos*: IceCube and its upgrade will tell us more about the origin of very high energy (PeV scale) astrophysical neutrinos. Energy spectrum, directional information, and flavor composition of these events can help us understand the astrophysical sources as well as neutrino properties. **(3)** *Neutrinos in cosmology*: Although indirect, neutrino masses inferred from cosmology would provide complementary information, and at the same time also test standard cosmological models.

(E) Underlying symmetries behind neutrino masses:

   (1) *Neutrino masses and physics beyond the Standard Model*: What can neutrino experiments teach us about the underlying symmetries of the theory that generates neutrino masses? Experiments in the intermediate time scale can lead to progress in this very basic question. **(2)** *Nucleon decay*: Ongoing large underground detectors (Super-Kamiokande) which are sensitive to neutrino oscillation physics continue to be also sensitive to nucleon decay. Discovery of nucleon decay would be monumental. **(3)** *Exotic neutrino properties*: Information on neutrino properties such as its magnetic moment, decay lifetime, possible violations of Lorentz invariance and/or CPT invariance, and its interactions with the dark matter sector would be valuable. Even if not found, neutrinos can provide some of the best tests of these fundamental symmetries.

References

[1] Chao Zhang. Recent Results From The Daya Bay Experiment. 2015, 1501.04991.

[2] Y. Abe et al. Improved measurements of the neutrino mixing angle θ_{13} with the Double Chooz detector. *JHEP*, **1410**:86, 2014, 1406.7763.

[3] P. Adamson et al. Combined analysis of ν_μ disappearance and $\nu_\mu \rightarrow \nu_e$ appearance in MINOS using accelerator and atmospheric neutrinos. *Phys.Rev.Lett.*, **112**:191801, 2014, 1403.0867.

[4] K. Abe et al. Measurements of neutrino oscillation in appearance and disappearance channels by the T2K experiment with 6.6×10^{20} protons on target. 2015, 1502.01550.

[5] Roger Wendell. Atmospheric Results from Super-Kamiokande. 2014, 1412.5234.

[6] John F. Beacom and Mark R. Vagins. GADZOOKS! Anti-neutrino spectroscopy with large water Cherenkov detectors. *Phys.Rev.Lett.*, **93**:171101, 2004, hep-ph/0309300.

[7] M.G. Aartsen et al. Determining neutrino oscillation parameters from atmospheric muon neutrino disappearance with three years of IceCube DeepCore data. 2014, 1410.7227.

[8] T. Walton et al. Measurement of muon plus proton final states in ν_μ Interactions on Hydrocarbon at $< E_\nu > = 4.2$ GeV. 2014, 1409.4497.

[9] H. Berns et al. The CAPTAIN Detector and Physics Program. 2013, 1309.1740.

[10] Marek Gazdzicki. Recent results from NA61/SHINE. 2014, 1412.4243.

[11] S. Bhadra et al. Letter of Intent to Construct a nuPRISM Detector in the J-PARC Neutrino Beamline. 2014, 1412.3086.

[12] M. Martini, M. Ericson, and G. Chanfray. Neutrino quasielastic interaction and nuclear dynamics. *Phys.Rev.*, **C84**:055502, 2011.

[13] O. Lalakulich, U. Mosel, and K. Gallmeister. Energy reconstruction in quasielastic scattering in the MiniBooNE and T2K experiments. *Phys.Rev.*, **C86**:054606, 2012, 1208.3678.

[14] R. Shneor et al. Investigation of proton-proton short-range correlations via the C-12(e, e' pp) reaction. *Phys.Rev.Lett.*, **99**:072501, 2007, nucl-ex/0703023.

[15] G. T. Garvey, D. A. Harris, H. A. Tanaka, R. Tayloe, and G. P. Zeller. Recent advances and open questions in neutrino-induced quasi-elastic scattering and single photon production. 2014, 1412.4294. Institute of Nuclear Theory workshop INT-13-54W.

[16] O. Benhar, F. Garibaldi, G.M. Urciuoli, C. Mariani, C.M. Jen, et al. Measurement of the Spectral Function of ^{40}Ar through the $(e, e'p)$ reaction. 2014, 1406.4080.

[17] H. Murayama J.N. Bahcall and C. Pena-Garay. What can we learn from neutrinoless double beta decay experiments? *Phys.Rev.*, **D70**:033012, 2004, hep-ph/0403167.

[18] Ben Monreal and Joseph Formaggio. Relativistic Cyclotron Radiation Detection of Tritium Decay Electrons as a New Technique for Measuring the Neutrino Mass. *Phys.Rev.*, **D80**:051301, 2009, 0904.2860.

[19] D.M. Asner et al. Single electron detection and spectroscopy via relativistic cyclotron radiation. 1408.5362.

[20] J. A. Formaggio, E. Figueroa-Feliciano, and A.J. Anderson. Sterile neutrinos, coherent scattering and oscillometry measurements with low-temperature bolometers. *Phys.Rev.*, **D85**:013009, 2012, 1107.3512.

[21] Pilar Coloma, Patrik Huber, and J. M. Link. Combining dark matter detectors and electron-capture sources to hunt for new physics in the neutrino sector. *JHEP*, **1411**:42, 2014, 1406.4914.

[22] D. Akimov et al. Coherent scattering investigations at the spallation neutron source: a snowmass white paper. 1310.0125.

[23] S.J. Brice et al. A method for measuring coherent elastic neutrino-nucleus scattering at a far off-axis high-energy neutrino beam target. *Phys.Rev.*, **D89**:072004, 2014, 1311.5958.

[24] A. de Gouvea et al. Intensity Frontier Neutrino Working Group Collaboration. 2013, 1310.4340.

[25] R. Acciarri et al. A Proposal for a Three Detector Short-Baseline Neutrino Oscillation Program in the Fermilab Booster Neutrino Beam. 2015, 1503.01520.

[26] I. Anghel et al. Expression of Interest: The Atmospheric Neutrino Neutron Interaction Experiment (ANNIE). 2014, 1402.6411.

[27] http://psec.uchicago.edu/.

[28] R. Dharmapalan et al. Low Mass WIMP Searches with a Neutrino Experiment: A Proposal for Further MiniBooNE Running. 2012, 1211.2258.

[29] R.T. Thornton. Accelerator-Produced Dark Matter Search using MiniBooNE. 2014, 1411.4311.

[30] F. Reines, C.L. Cowan, F.B. Harrison, A.D. McGuire, and H.W. Kruse. Detection of the free anti-neutrino. *Phys.Rev.*, **117**:159, 1960.

[31] S. Abe et al. Precision Measurement of Neutrino Oscillation Parameters with KamLAND. *Phys.Rev.Lett.*, **100**:221803, 2008, 0801.4589.

[32] Y. Abe et al. Reactor electron antineutrino disappearance in the Double Chooz experiment. *Phys.Rev.*, **D86**:052008, 2012, 1207.6632.

[33] F.P. An et al. Spectral measurement of electron antineutrino oscillation amplitude and frequency at Daya Bay. *Phys.Rev.Lett.*, **112**:061801, 2014, 1310.6732.

[34] G. Mention, M. Fechner, Th. Lasserre, Th.A. Mueller, D. Lhuillier, et al. The Reactor Antineutrino Anomaly. *Phys.Rev.*, **D83**:073006, 2011, 1101.2755.

[35] C. Zhang, X. Qian, and P. Vogel. Reactor Antineutrino Anomaly with known θ_{13}. *Phys.Rev.*, **D87**:073018, 2013, 1303.0900.

[36] M. Wolinska-Cichocka et al. *Nucl. Data Sheets*, 120:22, 2014.

[37] A. Fijalkowska et al. *Nucl. Data Sheets*, 120:26, 2014.

[38] K. Rykaczewski. 2015. Beta-strength, decay heat and antineutrino energy spectra from total absorption spectroscopy at ORNL, talk given in *The status of Reactor Antineutrino Flux Modelling*, Mines, Nantes.

[39] C. Lane, S.M. Usman, J. Blackmon, C. Rasco, H.P. Mumm, et al. A new type of Neutrino Detector for Sterile Neutrino Search at Nuclear Reactors and Nuclear Nonproliferation Applications. 2015, 1501.06935.

[40] J. Ashenfelter et al. PROSPECT - A Precision Reactor Oscillation and Spectrum Experiment at Short Baselines. 2013, 1309.7647.

[41] A.B. Balantekin, Henry Band, Russell Betts, Jeff J. Cherwinka, J.A. Detwiler, et al. Neutrino mass hierarchy determination and other physics potential of medium-baseline reactor neutrino oscillation experiments. 2013, 1307.7419.

[42] G. Bellini et al. SOX: Short distance neutrino Oscillations with BoreXino. *JHEP*, **1308**:038, 2013, 1304.7721.

[43] A. Gando et al. CeLAND: search for a 4th light neutrino state with a 3 PBq 144Ce-144Pr electron antineutrino generator in KamLAND. 2013, 1312.0896.

[44] M. Harada, S. Hasegawa, Y. Kasugai, S. Meigo, K. Sakai, et al. Proposal: A Search for Sterile Neutrino at J-PARC Materials and Life Science Experimental Facility. 2013, 1310.1437.

[45] J. Spitz. A Sterile Neutrino Search with Kaon Decay-at-rest. *Phys.Rev.*, **D85**:093020, 2012, 1203.6050.

[46] J. Spitz. Cross Section Measurements with Monoenergetic Muon Neutrinos. *Phys.Rev.*, **D89**:073007, 2014, 1402.2284.

[47] A. Bungau, A. Adelmann, J.R. Alonso, W. Barletta, R. Barlow, et al. Proposal for an Electron Antineutrino Disappearance Search Using High-Rate ^{8}Li Production and Decay. *Phys.Rev.Lett.*, **109**:141802, 2012, 1205.4419.

[48] J.M. Conrad and M.H. Shaevitz. Electron Antineutrino Disappearance at KamLAND and JUNO as Decisive Tests of the Short Baseline $\bar{\nu}_\mu \to \bar{\nu}_e$ Appearance Anomaly. *Phys.Rev.*, **D89**:057301, 2014, 1310.3857.

[49] M. Elnimr et al. The OscSNS White Paper. 2013, 1307.7097.

[50] C.A. Duba et al. HALO: The helium and lead observatory for supernova neutrinos. *J.Phys.Conf.Ser.*, **136**:042077, 2008.

4 WINP Agenda

http://www.bnl.gov/winp/

Wednesday February 4 morning plenary (Goals, Objectives, Background)

0)	Registration		08:00-17:00
1)	Welcome	Tribble	08:30-08:40
2)	View from the Funding Agencies:		
3)	WINP goals/overview of working groups	Kettell	09:10-09:30
4)	The Neutrino Landscape	Marciano	09:30-10:00
5)	What can we learn in the next 10 years	de Gouvea	10:00-10:30
	Coffee break		**10:30-10:45**
6)	Expected physics output of ongoing experiments	Thomson	10:45-11:15
7)	Short Baseline program at FNAL	Wilson	11:15-11:35
8)	What is needed for next LBN experiments	Worcester	11:35-11:55
	Workshop picture		**12:00**
	Lunch (on your own)		**12:15**

Wednesday February 4 afternoon plenary (Summaries of proposed initiatives)

9)	Summary of upgrades to existing experiments	Klein	13:30-14:15
10)	Large experiments needing R&D or US participation	Svoboda	14:15-15:00
	Coffee break		**15:00-15:30**
11)	Summary of small/midscale experiments	Scholberg	15:30-16:15
12)	Discussion	Patterson/Fleming	16:15-17:30
	Reception		17:30-19:30

Thursday February 5 morning Physics topics working group (parallel)

1)	Sterile ν	Huber/ Louis/Link/Littlejohn	08:30-12:30
2)	3-ν mixing	Gonzalez-Garcia/Whitehead/Cowen	08:30-12:30
3)	ν interactions	Morfin/Garvey	08:30-12:30
4)	ν properties	Kolomensky/Monreal	08:30-12:30
5)	Astrophysical ν	Vagins/Sullivan	08:30-12:30
	Coffee break		**10:30-11:00**
	Lunch (on your own)		**12:30**

Thursday February 5 afternoon techniques/approach/technology working groups (parallel)

6)	Short Baseline accelerator neutrinos	Schmitz/Guglielmi/Rameika	13:30-17:30
7)	Reactor ν	Heeger/Qian	13:30-17:30
8)	Source, cyclotron & meson decay at rest	Barbeau/Shaevitz/Maricic	13:30-17:30
9)	Detector R&D	Nessi/Stewart/Orebi-Gann/Sanchez	13:30-17:30
10)	Theory	Chen/Babu	13:30-17:30
	Coffee break		**15:00-15:30**
	Dinner (included in registration fee)		18:30-20:00

Friday February 6 Plenary (Working Group reports)

1)	Bullet points from sterile ν WG convenors		WG#1	08:30-08:45
2)	"	3ν-mixing WG	WG#2	08:45-09:00
3)	"	ν interactions WG	WG#3	09:00-09:15
4)	"	ν properties WG	WG#4	09:15-09:30
5)	"	Astrophysical ν WG	WG#5	09:30-09:45
6)	"	SBN WG	WG#6	09:45-10:00
7)	"	Reactor ν WG	WG#7	10:00-10:15
8)	"	source, cyclotron & DAR WG	WG#8	10:15-10:30
	Coffee break			**10:30-11:00**
9)	"	Detector R&D WG	WG#9	11:00-11:15
10)	"	Theory WG	WG#10	11:15-11:30
11)	"	experiment upgrade convenor		11:30-11:45
12)	"	large experiment convenor		11:45-12:00
13)	"	small/midscale experiment convenor		12:00-12:15
	Lunch (on your own)			**12:15**

Friday February 6 afternoon plenary (Summary)

14)	Discussion/Conclusions	Lykken/Blucher	14:00-16:00

5 Experimental Questionaire Responses

Responses from experiments to the WINP questionaire follow.
(see also `https://indico.bnl.gov/conferenceDisplay.py?confId=918`)

1. ANNIE
2. ARA
3. ASDC (Theia)
4. CAPTAIN
5. CENNS
6. CeSOX
7. CHIPS
8. COHERENT
9. Cr51
10. CUORE
11. DAEdALUS
12. DayaBay
13. ELBNF
14. Hyper-K
15. IceCube
16. IsoDAR
17. Jinping
18. JPARC56
19. JUNO
20. KamLAND
21. KATRIN
22. LAr35ton
23. LAr-CERN-prototype
24. LArIAT
25. MINERvA
26. MINOS
27. NESSiE
28. nEXO
29. NEXT
30. NuLAT
31. NuPRISM
32. OscSNS
33. PINGU
34. Project-8
35. PROSPECT
36. RICOCHET
37. SBN-ICARUS
38. SBN-LAr1-ND
39. SNO+
40. Super-Kamiokande
41. Super-NEMO-Demonstrator
42. US-NA61
43. WATCHMAN