Executive Summary

Introduction

The Department of Energy (DOE) Office of Science (SC) is planning investments in the next generation neutrino experiment, the Long-Baseline Neutrino Experiment (LBNE).

In light of the current budget climate, on March 19th, Dr. W.F. Brinkman, Director of the DOE Office of Science, asked Fermilab to find a path forward to reach the goals of the LBNE in a phased approach or with alternative options. His letter notes that this decision is not a negative judgment about the importance of the science, but rather it is a recognition that the peak cost of the project cannot be accommodated in the current budget climate, or that projected for the next decade. Pier Oddone, Director of Fermilab, formed a Steering Committee and two working groups, a Physics Working Group and an Engineering/Cost Working Group, to address this request. The Steering Committee is charged to provide guidance to the working groups, to identify viable options and to write the report to the DOE. The Physics Working Group is charged to analyze the physics reach of various phases and alternatives on a common basis, and the Engineering/Cost Working Group is charged to provide cost estimates and to analyze the feasibility of the proposed approaches with the same methodology. Dr. Brinkman's letter to Pier Oddone is given in *Appendix A*, and the membership of the Steering Committee, the committee's ex-officio members and the membership of the working groups are listed in *Appendix B*.

The Steering Committee produced an interim report and presented it to Pier Oddone on June 4. Pier Oddone briefed the interim conclusions to Dr. Brinkman on June 6. On June 29, Dr. Brinkman wrote a letter to Pier Oddone, asking the laboratory to proceed with planning a Critical Decision 1 review later this year based on the reconfigured LBNE options that we presented. Dr. Brinkman's letter is given to *Appendix C*.

The Steering Committee had twelve conference call meetings and had two face-to-face meetings on April 26, 2012 and May 22-23, 2012 at Fermilab. The Steering Committee organized and held a workshop on April 25-26, 2012 at Fermilab to inform the high-energy physics community, to discuss the status of the work in progress and to seek input from the community. *Appendix D* gives the agenda for the workshop. The Physics Working Group and the Engineering/Cost Working Group enlisted the necessary experts from Fermilab, other national laboratories, universities and the LBNE and other neutrino experiment collaborations to carry out the studies. Each working group provided a report of their analysis and their reports can be found at http://www.fnal.gov/directorate/ lbne_reconfiguration/. Meeting agendas and minutes of the Steering Group and the working groups, and the workshop presentations are posted on the LBNE reconfiguration webpage (http://www.fnal.gov/directorate/lbne_reconfiguration/).

The Steering Committee wishes to thank the Physics Working Group, the Engineering/Cost Working Group and many experts who participated in the studies, whose work is the foundation of this report. The committee would also like to thank those who provided their input to this process via presenting at the workshop or writing letters to the committee.

Neutrinos and LBNE

The discovery that neutrinos spontaneously change type – a phenomenon called neutrino oscillation – was one of the most revolutionary particle-physics discoveries of the last several decades. This discovery was unexpected by the very successful Standard Model of particle physics. It points to new physics phenomena at energies much higher than those that can directly be discovered at particle colliders, and it raises other challenging questions about the fundamental workings of the universe.

Neutrinos are the most elusive of the known fundamental particles. To the best of our knowledge, they interact with other particles only through the weak interactions. For this reason, neutrinos can only be observed and studied via intense neutrino sources and large detectors. Particle accelerators, nuclear reactors, cosmic ray air showers, and neutrinos originating in the sun and in supernovae provide important neutrino sources, and have all played critical roles in discovering neutrinos and their mysterious properties. These discoveries led to the 1988 Nobel Prize in Physics (Leon Lederman, Melvin Schwartz and Jack Steinberger), the 1995 Nobel Prize in Physics (Frederick Reines), and the 2002 Nobel Prize in Physics (Raymond Davis and Masatoshi Koshiba).

The experimental achievements of the past 15 years have been astonishing. A decade ago, the space of allowed oscillation parameters spanned many orders of magnitude. Within the three-neutrino picture, allowed regions have now shrunk to better than the 10% precision level for most of the parameters. By the end of this decade, invaluable new information is expected from the current generation of neutrino-oscillation experiments, namely the long-baseline beam experiments NOvA, T2K, MINOS, ICARUS and OPERA and the reactor experiments Double Chooz, Daya Bay and RENO. These experiments will measure the known oscillation parameters much more precisely, and may provide nontrivial hints regarding the neutrino mass hierarchy. However, it is unlikely that these experiments will be able to determine the ordering of the neutrino masses unambiguously, nor provide any significant information regarding possible violation of CP-invariance in the lepton sector. Nor is it expected that they will be able to test definitively the standard three-neutrino paradigm. That will be the task of next-generation experiments.

Future opportunities for testing the paradigm and probing new physics using next-generation neutrino-oscillation experiments are broad and exciting. The focus for the U.S. has been the Long Baseline Neutrino Experiment (LBNE), which would employ a 700 kW beam from Fermilab and a large liquid argon time-projection chamber at the Homestake mine in South Dakota, 1,300 km away. With the 1,300 km baseline, a broad-band neutrino beam designed specifically for this purpose, and the highly capable detector, LBNE would measure many of the oscillation parameters to high precision and, in a single experiment, test the internal consistency of the three-neutrino oscillation model. Placed deep underground, the detector would also allow for a rich physics program beyond neutrino-oscillation studies. It would include a high-sensitivity search for proton decay, and high-sensitivity studies of neutrinos coming from supernovae within our galaxy.

The LBNE would answer a number of important scientific questions:

1. Is there CP violation in the neutrino sector? The existence of matter this late in the universe's development requires CP violation at an early stage, but the amount seen in the quark sector is much too small to account for the matter that we observe in the universe. CP violation in the lepton sector may provide the explanation.
2. Is the ordering of the neutrino mass states the same as that of the quarks, or is the order inverted? In addition to being an important question on its own, the answer has a major

impact on our ability to determine whether the neutrino is its own antiparticle. If true, it could reflect physics at energy scales much greater than those probed at the LHC.

3. Is the proton stable? Proton decay would require violation of baryon number conservation, and such violation is needed to account for the matter-antimatter asymmetry in the universe. The answer will provide clues to the unification of the forces of nature.
4. What physics and astrophysics can we learn from the neutrinos emitted in supernova explosions?

The importance of these questions and the unique ability of LBNE to address them led to strong support by the scientific community for LBNE. LBNE was a feature of the plan proposed by the Particle Physics Project Prioritization Panel (P5) of the High Energy Physics Advisory Panel (HEPAP) in 2008 and was a key element of the strong endorsement for underground physics by the National Research Council, in July, 2011. The importance of LBNE to U.S leadership in neutrino physics was also recognized in the report of the DOE-sponsored workshop on Fundamental Physics at the Intensity Frontier, held in December 2011.

A very strong collaboration formed around LBNE with the participation of 65 institutions, including 6 U.S. national laboratories, from 5 countries.

Conclusions

To achieve all of the fundamental science goals listed above, a reconfigured LBNE would need a very long baseline (>1,000 km from accelerator to detector) and a large detector deep underground. However, it is not possible to meet both of these requirements in a first phase of the experiment within the budget guideline of approximately $700M – $800M, including contingency and escalation. The committee assessed various options that meet some of the requirements including underground detector only options (no accelerator-base neutrino beam) and a range of baselines from the existing 700-800 km available with Fermilab's NuMI beam to as far as 2,600 km, and identified three viable options for the first phase of a long-baseline experiment that have the potential to accomplish important science at realizable cost. These options are (not priority ordered):

- Using the existing NuMI beamline in the low energy configuration with a **30 kton** liquid argon time projection chamber (LAr-TPC) **surface detector** 14 mrad off-axis at Ash River in Minnesota, **810 km** from Fermilab.

- Using the existing NuMI beamline in the low energy configuration with a **15 kton** LAr-TPC **underground (at the 2,340 ft level) detector** on-axis at the Soudan Lab in Minnesota, **735 km** from Fermilab.

- Constructing a new low energy LBNE beamline with a **10 kton** LAr-TPC **surface detector** on-axis at Homestake in South Dakota, **1,300 km** from Fermilab.

The committee looked at possibilities of projects with significantly lower costs and concluded that the science reach for such projects becomes marginal.

We list pros and cons of each of the viable options below (not priority ordered).

- 30 kton surface detector at Ash River in Minnesota (NuMI low energy beam, 810 km baseline)

<table>
<tr><td>Pros</td><td>Best Phase 1 CP-violation sensitivity in combination with NOvA and T2K results for the current value of θ_{13}. The sensitivity would be enhanced if the mass ordering were known from other experiments.
Excellent (3σ) mass ordering reach in nearly half of the δ_{CP} range.</td></tr>
<tr><td>Cons</td><td>Narrow-band beam does not allow measurement of oscillatory signature.
Shorter baseline risks fundamental ambiguities in interpreting results.
Sensitivity decreases if θ_{13} is smaller than the current experimental value.
Cosmic ray backgrounds: impact and mitigation need to be determined.
Only accelerator-based physics.
Limited Phase 2 path:
Beam limited to 1.1 MW (Project X Stage 1).
Phase 2 could be a 15-20 kton underground (2,340 ft) detector at Soudan.</td></tr>
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- 15 kton underground (2,340 ft) detector at the Soudan Lab in Minnesota (NuMI low energy beam, 735 km baseline)

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<tr><td>Pros</td><td>Broadest Phase 1 physics program:
Accelerator-based physics including good (2σ) mass ordering and good CP-violation reach in half of the δ_{CP} range. CP-violation reach would be enhanced if the mass ordering were known from other experiments.
Non-accelerator physics including proton decay, atmospheric neutrinos, and supernovae neutrinos.
Cosmic ray background risks mitigated by underground location.</td></tr>
<tr><td>Cons</td><td>Mismatch between beam spectrum and shorter baseline does not allow full measurement of oscillatory signature.
Shorter baseline risks fundamental ambiguities in interpreting results. This risk is greater than for the Ash River option.
Sensitivity decreases if θ_{13} is smaller than the current experimental value.
Limited Phase 2 path:
Beam limited to 1.1 MW (Project X Stage 1).
Phase 2 could be a 30 kton surface detector at Ash River or an additional 25-30 kton underground (2,340 ft) detector at Soudan.</td></tr>
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- 10 kton surface detector at Homestake (new beamline, 1,300 km baseline)

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<tr><td>Pros</td><td>Excellent (3σ) mass ordering reach in the full δ_{CP} range.
Good CP violation reach: not dependent on a priori knowledge of the mass ordering.
Longer baseline and broad-band beam allow explicit reconstruction of oscillations in the energy spectrum: self-consistent standard neutrino measurements; best sensitivity to Standard Model tests and non-standard neutrino physics.
Clear Phase 2 path: a 20 – 25 kton underground (4850 ft) detector at the Homestake mine. This covers the full capability of the original LBNE physics program.
Takes full advantage of Project X beam power increases.</td></tr>
<tr><td>Cons</td><td>Cosmic ray backgrounds: impact and mitigation need to be determined.
Only accelerator-based physics. Proton decay, supernova neutrino and atmospheric neutrino research are delayed to Phase 2.
~10% more expensive than the other two options: cost evaluations and value engineering exercises in progress.</td></tr>
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The LBNE collaboration has conducted initial studies to verify whether the cosmic ray backgrounds are manageable for the operation of LAr-TPCs on the surface. The studies were concentrated on photon induced cascades as the major source of background events, as this is potentially the most serious problem. Two independent techniques have been investigated to reduce these backgrounds using the ability of the LAr detector to reconstruct muon tracks and electron showers and separate electron- from gamma-induced showers. Both techniques have been shown to be viable, even without the assumption of a photon trigger system or fast timing veto. It was found that a combination of simple cuts together with the low (2%) expected probability of e-γ misidentication can reject this background to a level well below the expected ν_e appearance signal. Studies will continue in the next few months. In addition, the shorter drift distance for surface options is chosen to mitigate the effects of space charge build-up due to cosmic rays. Detailed information is documented and available at http://www.fnal.gov/directorate/lbne_reconfiguration/.

The Phase 1 experiment will use the existing detectors (MINOS near detector, MINERvA, and NOvA near detector) as near detectors for the two NuMI options, and use muon detectors to monitor the beam for the Homestake option. For the Homestake case, the LBNE collaboration has examined strategies to maintain the initial scientific performance without a full near detector complex. Although detailed evaluation must await full simulations, the conclusion is that there are viable strategies that will be adequate for the initial period of LBNE running. However, a complete LBNE near detector system will be required in a later stage to achieve the full precision of the experiment. Studies will continue as the design of LBNE is developed. Details information is documented and available at http://www.fnal.gov/directorate/lbne_reconfiguration/.

Studies have been done to understand the possibilities for optimizing the NuMI beamline for a lower-neutrino-energy spectrum and a higher flux to enhance the physics sensitivity for the two NuMI options. The conclusion is that modest increases in the flux below 2 GeV are possible, but that no options for large gains are known. Detailed information is documented and available at http://www.fnal.gov/directorate/lbne_reconfiguration/.

While each of these first-phase options is more sensitive than the others in some particular physics domain, the Steering Committee in its discussions strongly favored the option to build a new beamline to Homestake with an initial 10 kton LAr-TPC detector on the surface. The physics reach of this first phase is very strong; it would determine the mass hierarchy and explore the CP-violating phase δ_{CP}, and measure other oscillation parameters: θ_{13}, θ_{23}, and $|\Delta m^2_{32}|$. Moreover this option is seen by the Steering Committee as a start of a long-term world-leading program that would achieve the full goals of LBNE in time and allow probing the Standard Model most incisively beyond its current state. Subsequent phases will include:

- A highly capable near neutrino detector, which will reduce systematic errors on the oscillation measurements and enable a broad program of short-baseline neutrino physics.
- An increase in far detector mass to 35 kton fiducial mass placed at the 4850 ft level, which will further improve the precision of the primary long-baseline oscillation measurements, enable measurement of more difficult channels to make a fully comprehensive test of the three-neutrino mixing model, and open or enhance the program in non-accelerator-based physics, including searches for baryon-number-violating processes and measurements of supernova neutrinos.
- A staged increase in beam power from 700 kW to 2.3 MW with the development of Project X, which will enhance the sensitivity and statistical precision of all of the long- and short-baseline neutrino measurements.

The actual order and scope of the subsequent stages would depend on where the physics leads and the available resources.

At the present level of cost estimation, it appears that this preferred option may be ~15% more expensive than the other two options, but cost evaluations and value engineering exercises are continuing.

Although the preferred option has the required very long baseline, the major limitation of the preferred option is that the underground physics program including proton decay and supernova collapse cannot start until later phases of the project. Placing a 10 kton detector underground instead of the surface in the first phase would allow such a start, and increase the cost by about $135M.

Establishing a clear long-term program will make it possible to bring in the support of other agencies both domestic and foreign. The opportunities offered by the beam from Fermilab, the long baseline and ultimately underground operation are unique in the world. Additional national or international collaborators have the opportunity to increase the scope of the first phase of LBNE or accelerate the implementation of subsequent phases. In particular, partnerships with institutions and agencies could add sufficient additional resources to place the initial 10 kton LAr TPC detector 4850 feet underground and provide a full near detector in the first phase. Studies of proton decay and neutrinos from supernova collapse are complementary to those being performed with existing water Cerenkov detectors. For the study of supernova collapse, LAr TPCs are sensitive to neutrinos whereas water Cerenkov detectors are sensitive to antineutrinos; for the study of proton decay, the LAr TPC is much more sensitive to the decay of protons into kaons as preferred by supersymmetric theories. There are also a large number of other nucleon decay modes for which liquid argon has high detection efficiency. Detection of even a single event in any of these modes would be revolutionary for particle physics.