Volume 1

The Long-Baseline Neutrino Experiment (LBNE)

May 5, 2005 DRAFT

NOTE: All figures are placeholders in this draft

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Acronyms and Abbreviations

AC	Alternating Current
Access	Database program from Microsoft Corporation
ACWP	Actual Cost of Work Performed
ADC	Analog-to-Digital Converter
AGS	Alternate Gradient Synchrotron
ALD	Associate Laboratory Director
APS	American Physical Society
ATLAS	A Toroidal LHC Apparatus
BAC	Budget at Completion
BCP	Baseline Change Proposal
BCWP	Budgeted Cost for Work Performed
BCWS	Budgeted Cost for Work Scheduled
BNL	Brookhaven National Laboratory
BO	Beneficial Occupancy
CAIRS	Computerized Accident Incident Recordkeeping and Reporting System
CAM	Control Account Manager
CC	Charged-Current Neutrino Interactions
CCB	Change Control Board
CCD	Charge-Coupled Device
CD	Computing Division
CD-0	Critical Decision-0
CD-1	Critical Decision-1
CD-2	Critical Decision-2
CD-3	Critical Decision-3
CD-4	Critical Decision-4
CDR	Conceptual Design Report
CERN	European Organization for Nuclear Research
C.L.	Confidence Level
CP	Charge-Parity Symmetry
CPT	Charge-Parity Time Reversal Symmetry
DAC	Digital-to-Analog Converter
DAQ	Data Acquisition
DC	Direct Current
DCR	Document Change Request
DOE	Department of Energy
DPM	Deputy Project Manager
DUSEL	Deep Underground Science and Engineering Laboratory
EAC	Estimates at Completion
ES	Elastic Neutrino Scattering
ES&H	Environment, Safety and Health
FADC	Flash Analog-to-Digital Converter
FEA	Finite Element Analysis
FEC	Front-End Card
FEE	Front-End Electronics
Fermilab	Fermi National Accelerator Laboratory
FET	Field Effect Transistor
FNAL	Fermi National Accelerator Laboratory
FPD	Federal Project Director
FPGA	Field Programmable Gate Array

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FRA	Fermi Research Alliance, LLC
FSS	Facility Safety Systems
FWHM	Full Width at Half Maximum
FY	Fiscal Year
GEANT	Geometry and Tracking simulation software
GPS	Global Positioning System
HEP	High Energy Physics
HND	Homestake Neutrino Detector
HV	High Voltage
ISM	Integrated Safety Management
ISO	International Standards of Organization
JTAG	Joint Test Action Group
K2K	KEK to Kamiokande Neutrino Oscillation Experiment
KamLAND	Kamioka Liquid Scintillator Antineutrino Detector
KEK	High Energy Accelerator Research Organization in Japan
L1	Level 1
L2	Level 2
L3	Level 3
L4	Level 4
L/E	Distance divided by energy
LabVIEW	Laboratory Virtual Instrument Engineering Workbench
LAr20	Liquid Argon Detector
LArTPC	Liquid Argon Time Projection Chamber
LBNE	Long-Baseline Neutrino Experiment
LBNE-PM	Long-Baseline Neutrino Experiment Project Manager
LBNE-PO	Long-Baseline Neutrino Experiment Project Office
LBNL	Lawrence Berkeley National Laboratory
LED	Light Emitting Diode
LMA	Large Mixing Angle solution
LSND	Liquid Scintillator Neutrino Detector
LVDS	Low Voltage Differential
MBLT	Multiplexed Block Transfer
MC	Monte Carlo
MIE	Major Item of Equipment
MINOS	Main Injector Neutrino Oscillation Experiment
ML	Maximum Liklihood
MOU	Memorandum of Understanding
MR	Management Reserve
m.w.e.	Meters of Water Equivalent
NC	Neutral Current Neutrino Interactions
NEPA	National Environmental Protection Act
NSF	National Science Foundation
NTP	Network Time Protocol
NuSAG	Neutrino Science Assessment Group
ODH	Oxygen Deficiency Hazard
OPC	Other Project Costs
OPMO	Office of Project Management and Oversight
ORPS	Occurrence Reporting and Processing System
P5	Particle Physics Project Prioritization Panel
PA	Photomultiplier tube Assembly
PAP	Project Advisory Panel
PC	Personal Computer
p.e.	Photo-Electrons
PEP	Project Execution Plan
P-PEP	Preliminary Project Execution Plan
PIR	Panel of Institutional Representatives

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PIU	Photomultiplier tube Installation Unit
PLL	Phase-Locked Loop
PM	Project Manager
PMCS	Project Management Control System
PMG	Project Management Group
PMP	Project Management Plan
PMT	Photomultiplier Tube
PPD	Particle Physics Division
PSAD	Preliminary Safety Assessment Document
PSL	Physical Sciences Laboratory at the University of Wisconsin
PVC	Poly Vinyl Chloride
QA	Quality Assurance
QAP	Quality Assurance Plan
QC	Quality Control
QE	Quantum Efficiency
QM	Quality Management
R&D	Research and Development
RACF	RHIC and ATLAS Computing Facility
RHIC	Relativistic Heavy Ion Collider
RPVC	Rigid Poly Vinyl Chloride
RQD	Rock Quality Designation
RS	Richter Scale
RSL	Resource Loaded Schedule
SAD	Safety Assessment Document
SBMS	Standards Based Management System
SDSTA	South Dakota Science and Technology Administration
SM	System Manager
SNO	Sudbury Neutrino Observatory
SNO+	Proposed solar and geo-neutrino experiment using liquid scintillator in SNO detector
SOW	Statement of Work
s.p.e.	Single Photon-Electron
SS	Stainless Steel
SSO	Senior Safety Officer
SUSEL	Stanford Underground Science and Engineering Laboratory
SV	Schedule Variance
TB	Technical Board
TDC	Time-to-Digital Converter
TDR	Technical Design Report
TPC	Time Projection Chamber
TPC	Total Project Cost
UCT	Universal Coordinated Time
UV	Ultraviolet light
VAC	Variance at Completion
VME	Versa Module Europa
WBS	Work Breakdown Structure
WCD	Water Cherenkov Detector
WCD-PM	Water Cherenkov Detector Project Management
WCD-PO	Water Cherenkov Detector Project Office

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1 Executive Summary

1.1 Introduction

The Long-Baseline Neutrino Experiment (LBNE) Project Team has prepared this Conceptual Design Report for a world-class facility that will enable the scientific community to carry out a compelling research program in neutrino physics. The ultimate goal in the operation of the facility and experimental program is to measure fundamental physical parameters, explore physics beyond the Standard Model and better elucidate the nature of matter and antimatter.

Although the Standard Model of particle physics presents a remarkably accurate description of the elementary particles and their interactions, we know that the current model is incomplete and that a more fundamental underlying theory must exist. Results from the last decade revealing that the three known types of neutrinos have nonzero mass, mix with one another and oscillate between generations hint at physics beyond the Standard Model. Measuring the mass and other properties of neutrinos is fundamental to understanding this deeper underlying theory and will profoundly shape our understanding of the evolution of the universe.

In its 2008 report, the Particle Physics Project Prioritization Panel (P5) recommended a world-class neutrino physics program as a core component of the U.S. particle physics program. Included in the report is the long-term vision of a large detector in the proposed Deep Underground Science and Engineering Laboratory (DUSEL) and a high-intensity neutrino source at Fermi National Accelerator Laboratory (FNAL). On January 8, 2010, the Department of Energy approved the Mission Need for a new long-baseline neutrino experiment that would enable this world-class program and firmly establish the U.S. as the leader in neutrino science.

This document presents the conceptual design for the LBNE Project to carry out this Mission Need. LBNE would provide unprecedentedly precise neutrino oscillation measurements, allowing scientists to measure the value of the third mixing angle, determine the neutrino mass hierarchy and search for CP-violation in neutrinos. The preferred configuration of the LBNE facility, in which the large neutrino detector is located deep underground, could also provide opportunities for research in other areas of physics, such as nucleon decay and neutrino astrophysics.

1.2 Scope

The LBNE project scope includes construction of a facility comprised of a large detector illuminated by a distant, intense neutrino source and a much smaller detector located close to the source. The favored alternative for achieving the project's mission is aiming protons from the Fermilab Main Injector towards the NSF proposed DUSEL site at the Homestake Mine in Lead, South Dakota, located 1300 km from Fermilab. This configuration is the basis for the design

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presented in this Conceptual Design Report. Specifically, the main scope elements include:

- A proton beam aimed at the far detector site
- A neutrino beam aimed at the far detector site
- A near detector complex located near the neutrino source
- Massive neutrino detectors located at the far detector site

1.3 Capabilities

Elements of the LBNE Project are being designed to optimize the measurement of neutrino oscillations, in particular electron neutrino appearance at the far detector. The main performance characteristics of the major project elements are given in Table X. Detailed performance characteristics are presented in the respective volumes of the sub-projects.

1.4 Costs and Schedule

The Total Estimated Cost (TEC) of the LBNE Project is $XXX.X M. The Total Project Cost (TPC) is $YYY.Y M, which includes an NSF contribution of $ZZZ.Z M. The schedule for construction will lead to a start of operations in FY20??.

1.5 Acquisition Strategy

The acquisition strategy relies on Fermi Research Alliance (FRA), the Department of Energy Managing and Operating (M&O) contractor for Fermi National Accelerator Laboratory, to directly manage the elements of the LBNE Project. This will include all design, construction, fabrication, assembly, installation and pre-commissioning of project elements that will be located on the Fermilab site, as well as those at the far detector site, for which the Department of Energy is the steward.

[Additional material will be added based on the actual Acquisition Strategy that is developed by the Integrated Project Team (DOE + LBNE Project)]

Project Element	Performance Parameter

Table XX To be completed

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2 The LBNE Project Overview

2.1 Project Mission

Precise measurement of neutrino oscillations would allow for determination of the relative masses and mass ordering of the three known neutrinos and would provide valuable clues about questions unanswered in the Standard Model. Neutrino oscillation measurement would also allow for research into CP violation in the neutrino sector, which is possibly connected to the dominance of matter over antimatter in the universe.

To achieve precise neutrino oscillation measurements requires an intense neutrino beam and very large detectors. A large detector, if located underground and thus shielded from cosmic rays, could also provide an opportunity for increased science, including the search for proton decay and observation of neutrinos generated by supernovae. The LBNE project mission is to build an experimental facility in order to further our knowledge of neutrinos and work toward the discovery of new physics.

2.2 Project Scope

2.2.1 Overview

The LBNE project will be comprised of an intense neutrino source pointing toward a distant large detector and a much smaller detector located close to the source. The far detector must be a long distance from the neutrino source to increase sensitivity to neutrino oscillations. A nearby detector close to the neutrino source is necessary to measure the initial composition of the beam.

LBNE's targeted scope is to build a neutrino facility that uses a proton beam to produce a beam of neutrinos directed towards near and far detectors. Two 100-kT Water-Cherenkov-Equivalent (WCE) cavern/detector ensembles are being considered for the far detector. There are two favored technologies being explored for the far detector – water Cherenkov and liquid argon. Water Cherenkov detectors have been successfully operated underground at a number of sites. Alternatively, liquid argon detectors offer some advantages over water Cherenkov detectors, but research and development is still needed to prove their cost and effectiveness.

The preferred alternative for the neutrino source and near detector site is FNAL, as it has already developed the expertise for construction of neutrino beams as part of the NuMI/MINOS project. The 700-kW upgrade of the FNAL proton source, a component of the current NOνA project, offers a platform from which to launch a new neutrino beam for a long-baseline detector.

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The NSF proposed Deep Underground Science and Engineering Laboratory (DUSEL) site at Homestake Mine in Lead, South Dakota is the preferred alternative for the far detector site because it offers both sufficient depth for shielding from cosmic rays and an optimum distance from FNAL to detect neutrino oscillations.

2.2.2 Neutrino Beam Configuration

The key elements that define the neutrino beam configuration include the primary beam magnets, which transport the proton beam from the FNAL Main Injector and focus it onto a neutrino production target; magnetic horns, which focus pions produced at the target into a decay channel; and an absorber to stop the transport of un-interacted protons and hadrons that have not decayed.

The primary beam transport consists of dipole, quadrupole and corrector magnets, as well as vacuum, water and instrumentation control systems. The primary transport elements are configured such that at the location of the target, the beam is aimed at a downward angle of 5.6 degrees, or 10% slope, in the direction of the Homestake Mine in Lead, South Dakota. The remainder of the facility and components are constructed or installed in a manner to maintain this angle for the direction of the neutrino beam.

The primary proton beam will interact in a graphite target of length X, which, for normal operation of LBNE, is inserted into the first of two magnetic horns used to focus the pions produced in the target. The Target Hall houses the targets, horns, radiation shielding and equipment for handling the components. Following the Target Hall will be a decay pipe 4 m in diameter and 250 m in length, surrounded by 3 m of concrete shielding. An absorber will be installed following the decay tunnel, and a beam position monitor is installed behind the absorber. The reference design for the neutrino beam is described in Volume 2 of this Conceptual Design Report.

2.2.3 Near Detector Configuration

[This section will be written after the outline of Volume 3 is submitted.]

2.2.4 Far Detector Configurations

[This section will be re-written after Volumes 4 and 5 are complete and a decision on how to present the far detector configurations has been made.

For the May – June time frame, this section will present the configuration options that are being considered.]

Two different detector technologies are being pursued for the design of the far detector – water Cherenkov and liquid argon.

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While originally conceived for proton decay searches, large water Cherenkov detectors have been constructed and demonstrated to be a cost-effective detector for neutrinos as well [references]. The Super-Kamiokande II detector in Japan is a 50-kT total volume detector that has provided definitive measurements of solar and atmospheric neutrino parameters. It is currently the far detector for the JPARC neutrino beam program in pursuit of the measurement of the θ_{13} mixing angle [references]. Scaling the total mass of a water detector by a factor of two or three is deemed technically feasible, though challenging.

The largest liquid argon detector to operate to date is the 300-ton module of the ICARUS detector, which had a brief commissioning run in 200?. Currently, the two 300-ton ICARUS modules are being filled in the Gran Sasso Laboratory and will soon be capable of detecting neutrinos from the CNGS neutrino beam from CERN [references]. An integrated plan for liquid argon detectors has been underway at Fermilab for several years, and the design of a 20-kT module for an LBNE detector is a key component of this plan.

In Chapter 3, we will discuss in some detail the issue of the depth requirements for the far detector. Given the configuration of the underground spaces at the Homestake Mine, it is an obvious conclusion that a water Cherenkov detector should be located on the main DUSEL campus at 4850 ft The situation is not so clear for a liquid argon detector, and during the design phase both deep and shallow options are being developed.

The far detector configurations that have been developed during the LBNE post-CD-0 conceptual design phase are summarized in Table ??

Configuration	WCD @ 4850 ft	LAr @ 4830 ft	LAr @ 300 or 800 ft
a	2 x 100 kT		
b		2 x 20 kT	
c			2 x 20 kT
d	1 x 100 kT	1 x 20 kT	
e	1 x 100 kT		1 x 20 kT

Table ?? Five configurations being evaluated for the LBNE far detector configuration. 1 or 2 indicates the number of modules of the specified mss that would be placed at that depth.

2.2.5 Conventional Facilities

[In the following two sections, we briefly describe the scope of work for the civil construction activities at both sites.]

2.2.5.1 Conventional Facilities at Fermilab

Text goes here…

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2.2.5.2 Conventional Facilities at DUSEL

Text goes here…

2.3 Project Organization

The LBNE Project consists of five sub-projects, coordinated by a central project office located at FNAL:

1. The LBNE Neutrino Beamline
2. The LBNE Near Detectors
3. A Water Cherenkov Detector for LBNE
4. A Liquid Argon Detector for LBNE
5. Conventional Facilities

The FNAL project office is headed by the project manager and assisted by the project engineer and project scientist. Project office support staff include a chief financial officer, a lead project controls specialist, a documentation team and administrative support. The Neutrino Beamline, Liquid Argon and Conventional Facilities sub-projects are managed out of the FNAL project office, while the Near Detectors and Water Cherenkov sub-projects are managed out of project offices at Los Alamos National Laboratory and Brookhaven National Laboratory, respectively.

The LBNE project office has developed overriding plans for project management, risk management, configuration control and quality assurance [references]. The sub-projects have developed individually tailored plans as appropriate, and these are integrated into the overriding plans by reference and appendices.

A project organization chart is shown in Figure X.

2.4 Work Breakdown Structure

The LBNE Project Work Breakdown Structure to level 4 is shown in Figure ??
[Need to generate this Figure]

2.5 Cost and Schedule

[This section is a placeholder]. It will be configured correctly once we decide how the far detector configuration will be presented.]

A preliminary high-level summary of the cost of the LBNE Project, at the second level of the work breakdown structure, is given in Table ??.

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LBNE Level 2 Cost Element	Cost (FY10 ??)
1.1 Project Management	
1.2 Neutrino Beam	
1.3 Near Detector	
1.4 Water Cherenkov Far Detector	
1.5 Liquid Argon Far Detector	
1.6.1 Conventional Facilities at Fermilab	
1.6.2 Conventional Facilities at DUSEL	
LBNE Total Project Cost	

Table ?? Level 2/3 Cost Breakout for the LBNE Project

A preliminary Level 0 Milestone Schedule to construct the LBNE Project is shown in Table ??

Major Milestone Events	Preliminary Schedule
CD-0 (Approve Mission Need)	2nd Quarter 2010
CD-1 (Approve Alternative Selection and Cost Range)	
CD-2 (Approve Performance Baseline)	
CD-3 (Approve Start of Construction)	
CD-4 (Approve Start of Operations)	

Table??

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3 Science With LBNE

3.1 Overview

Particle physics has been very successful in creating a major synthesis of its findings, the Standard Model. At successive generations of particle accelerators in the U.S., Europe and Asia, physicists have used high-energy collisions to discover many new particles and make precision measurements of fundamental parameters. Simultaneously, scientists have carried out experiments to study naturally produced particles, such as the particles resulting from ultra-high-energy cosmic ray interactions and low-energy neutrinos emerging from the core of the sun. These efforts have uncovered both new principles and many unsuspected features of nature, resulting in an ever-increasing understanding of the workings of the universe.

In the past two decades, scientists have observed muon neutrinos produced in cosmic ray reactions in the earth's atmosphere and electron neutrinos produced in nuclear reactions in the sun's core change from one flavor to another between source and detection. Further experimentation with both natural neutrino sources and neutrinos from reactors and accelerators has confirmed that the neutrino flavor states do not remain constant in time, but rather oscillate with a frequency governed by the magnitude of the differences between the three mass states of neutrinos.

As the name implies, the primary science motivation for the LBNE project is to study the phenomena of accelerator-generated long-baseline neutrino oscillations. A detailed description of this experiment is presented in Section 2.3. As the reader will learn, to carry out this experiment, LBNE requires construction of very massive detectors, with masses of tens to hundreds of kilotons, depending on the specific technology of the detector. Locating these massive detectors deep underground, where they are shielded from backgrounds induced by cosmic ray interactions, provides the opportunity to extend the science goals to include searches for proton decay, supernovae, solar and atmospheric neutrinos and other rare phenomena.

The ability to have a broad range of physics capability has precedence in the history of underground detectors. Experimental programs initially implemented to search for proton decay have so far realized two significant successes in neutrino physics. The IMB [ref] and Kamiokande [ref] collaborations made an extremely impressive accidental discovery of supernova neutrinos in 1987, confirming the theory of supernova collapse. Subsequently, the physics program with Super-Kamiokande [ref] has been key to understanding solar and atmospheric neutrinos, including the definitive determination that neutrino oscillations were the explanation of the atmospheric neutrino anomaly [ref].

In the following sections, we describe the experimental searches that could be explored in the proposed LBNE detectors. These descriptions include the physics motivation, historical context and detector requirements to carry out each element of this program. Following the discussion of Accelerator Neutrino Oscillations in Section 2.3, Section 2.4 describes the means

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and methods for a next-generation search for proton decay. Section 2.5 explains how the LBNE detectors could be utilized to detect a supernova burst occurring in or near our galaxy. Section 2.6 proposes the means of possibly detecting the never-before-seen relic neutrinos from ancient and distant supernovae. [Note – as we gather requirements, we may end up combining burst and relic supernova neutrinos.] Section 2.6 describes a program of short-baseline physics that could be undertaken with the near detector complex described in Volume 3.

Section 2.7 discusses measurements that could be made with atmospheric and solar neutrinos, including possible determination of the neutrino mass hierarchy and the solar MSW day-night effect. This section also describes studies that could be undertaken to explore possible further exploitation of the LBNE detectors to include searches for more challenging or rare phenomena such as geo, reactor and ultra-high-energy neutrinos.

[Note for CDR development phase: this chapter includes placeholders for descriptions of the science case for each of the Topical Working Groups that has been set up. These sections will be developed as the Working Groups produce requirements and capabilities. The early drafts of this chapter will be based on text from previous studies and reports, but will be updated as a better analysis of the detector capabilities is produced.]

3.2 Detector Technologies for LBNE

3.2.1 Overview

[Describe the interactions that the detectors need to be able to detect, i.e. CC, NE, elastic scattering, inverse beta decay, etc. Describe the broad spectrum of energies that this program covers; all programs require large mass and good energy resolution. Summarize how the detector performance is a function of its depth (table from the depth document). Warn that low energy thresholds impose the need for enhancement of the detector, (i.e. gadolinium to enhance neutron capture, high phototube coverage and Q.E.,…) Introduce the general types of background that will be encountered, i.e. from NCπ^0 in beam physics to spallation backgrounds for low energy measurements…]

3.2.2 Water Cherenkov Detectors

The basic components of a water Cherenkov detector include a vessel to contain a large volume of water, which is the target material, and photomultiplier tubes (PMTs) lining the inner surface of the vessel to detect photons emitted by charged particles as they travel through the water. The charged particles result from background entering the detector or from interactions of neutrinos or other particles with the subatomic constituents of the water molecules. When these charged particles pass through the water with velocity greater than the speed of light in water[1], photons, called Cherenkov photons[2], are emitted in a cone around the direction of the particle's path. The emission angle for Cherenkov photons is given by:

[1] $v > c/n$, where c is the speed of light in vacuum and n is the index of refraction of water
[2] Historical context

$$\theta_c = \frac{1}{bnl}$$

where β is the particle's velocity with respect to *c*, and λ is the wavelength of the Cherenkov light. While Cherenkov photons are emitted with a continuum of wavelengths, PMTs have a specific narrow range of wavelengths over which they are sensitive. For relativistic particles (b~1), nearly pure water (n~1.33) and l~ ?nm, the Cherenkov angle is qc = 420. Again for b~1, several hundred photons per centimeter of travel will be generated in the wavelength range of PMT sensitivity.

As the Cherenkov photons travel through the water and arrive at the vessel wall, the conical nature of the emission leads to a pattern of rings detectable by the array of PMTs. Signals from the PMTs are readout with electronics consisting of charge-to-digital converters and time-to-digital converters. The PMT readouts are then used to analyze the arrival time and number of photons in a ring. From this information, the direction, origin and energy of the original track can be reconstructed.

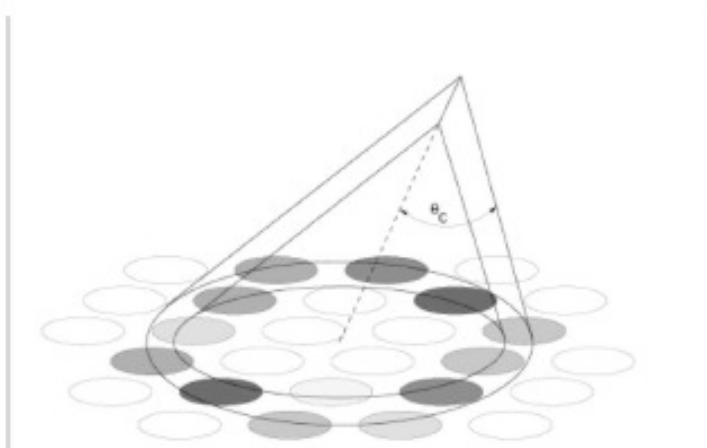


Figure ?? The Cherenkov light generated by the charged particle's path inside the detector arrives at the detector wall, where it produces a ring pattern that can be used to reconstruct the track's geometry and energy.

The direction, energy and flavor of a neutrino, ν, producing a charged current neutrino interaction,

$$\nu_l + N \text{®} \; l^- + X$$

within the detector volume may be reconstructed by measuring the direction, energy and flavor of the lepton, l . In a water Cherenkov detector muons can be distinguished from electrons by the pattern of light recorded by the PMTs. Because muons undergo very little scattering as they pass

through the water, the ring pattern has a very "neat" outer edge. In contrast, particles such as electrons and photons will undergo multiple scattering and showering as they travel, producing a very ragged edge to the pattern of light in the PMTs. Figure ?? shows these distinct muon and electron patterns for two events in the Super-Kamiokande detector. [Note – this figure should be replaced with LBNE MC events.]

[Add overview/summary discussion of signal detection efficiency, energy resolution and backgrounds.]

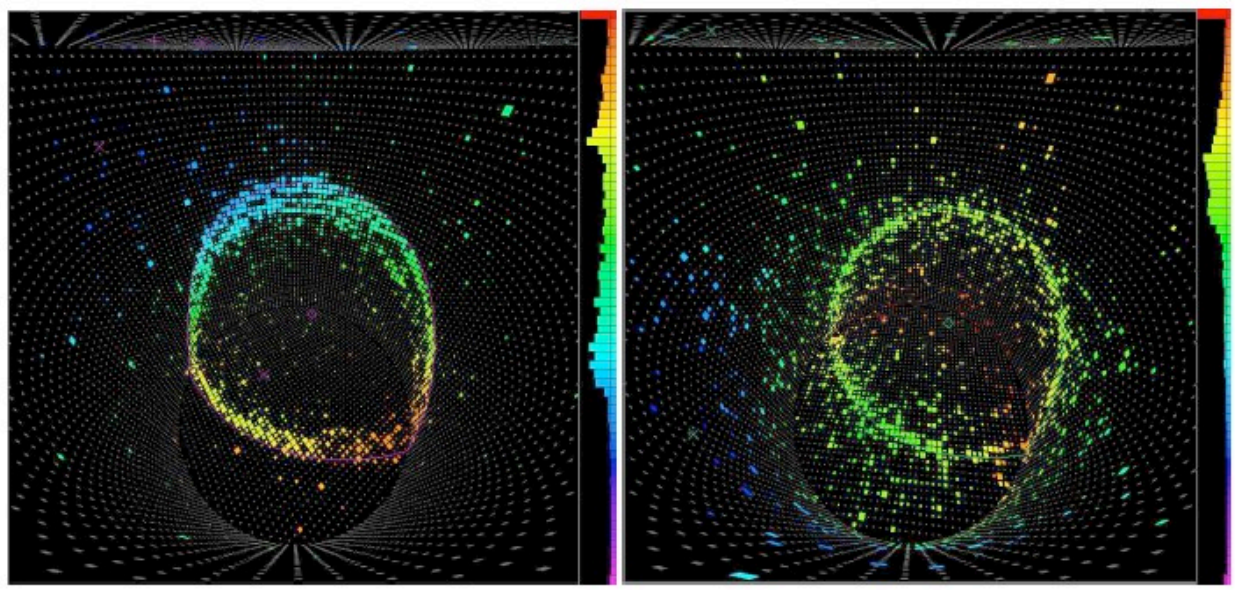


Figure ?? Two events displayed for the Super-Kamiokande detector. Left – muon, right – electron. To be replaced or supplemented by LBNE MC events

3.2.3 Liquid Argon Detectors

The basic components of a liquid argon detector include a cryostat, sets of cathode and anode planes, and readout electronics. The cryostat contains and maintains the liquid argon target material at a cryogenic temperature of 87 K. The sets of cathode and anode planes create a uniform electric field within the volume. The readout electronics on the anode planes record the passing charge of the ionization electrons created as charge particles drift through the liquid argon along the direction of the electric field. Figure ?? is an illustration of the basic idea. The set of planes is collectively called a Time Projection Chamber (TPC). The typical configuration of the anode wire planes is a set of two of three planes with 3 – 5 mm wire spacing. The wires are oriented with significant stereo angles with respect to each other. The first and second of the three planes are non-destructive to the passing charge and records the passing charge by induction. The final readout plane collects the charge from which the energy deposition can be determined. In addition to recording the induced or collected charge, the time of the arrival of the charge (relative to a t = 0 time stamp) is also recorded. By plotting the arrival time of a "hit" versus the wire numbers, a two-dimensional image of the event topology is created. Combining

the hits from multiple views allows one to construct three-dimensional tracks and hence a three dimensional image of the event. The energy deposition from the collection plane is displayed in the varying intensity of the displayed tracks. Display of the raw data from interactions in the ArgoNeuT detector[3] are shown in Figure ??

The topology of the tracks and the *dE/dx* along the track can be used to determine the type of event and its properties. For example, a cosmic ray muon will be reconstructed in the detector as a clear incoming track, whereas a neutrino interaction will create tracks that originate inside the chamber. Single electrons from the charged current interactions of ν_e can be differentiated from π^0 gamma rays by event topology and energy deposition in the first few centimeters of the event vertex.

[Add overview/summary discussion of signal detection efficiency, energy resolution and backgrounds.]

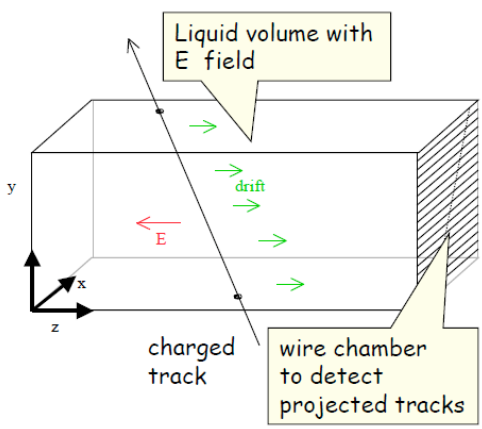
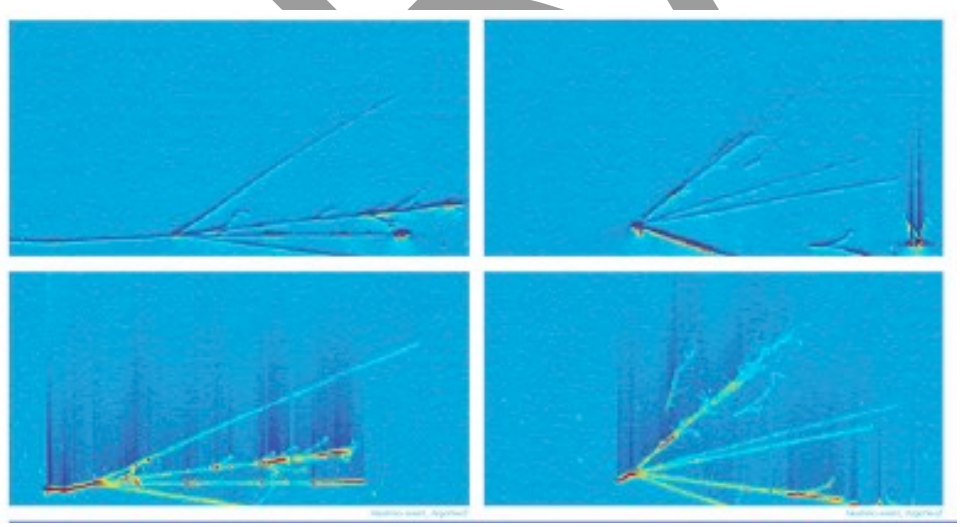


Figure ?? Schematic illustration of the basic principle of liquid argon detector [Need to make over following LBNE geometry…]



[3] ArgoNeuT is a 0.3-ton LArTPC which collected neutrino interactions in the NuMI beam in 2008. See reference xx.

Figure ?? Neutrino interactions in the ArgoNeut detector (PLACEHOLDER)

3.3 Detector Depth Requirements

3.3.1 Water Cherenkov Detectors

Text goes here…

3.3.2 Liquid Argon Detectors

Text goes here…

3.4 Accelerator Neutrino Oscillations

3.4.1 Historical Context

[This is a very brief summary of the discovery of neutrino oscillations in solar and atmospheric experiments under the two-neutrino hypothesis. Concludes with accelerator confirmation in K2K and MINOS and the ongoing numu-ntau search in OPERA.]

3.4.2 Three Neutrino Mass and Mixing

[This section presents the three neutrino mass-mixing matrix. We also present the full oscillation probability for numu to nue. Simplify it just showing what the parameters are. We define the mixing angle and the phase delta. A table summarizes the current measurements of the angles and delta m-squares. We introduce the concept of the mass hierarchy. Includes the mass splitting figure. Conclusion – introduce the idea that theta13 must be measureable to the level of ~0.01 to proceed to experimentally determine mass hierarchy or delta via this method (accelerator)]

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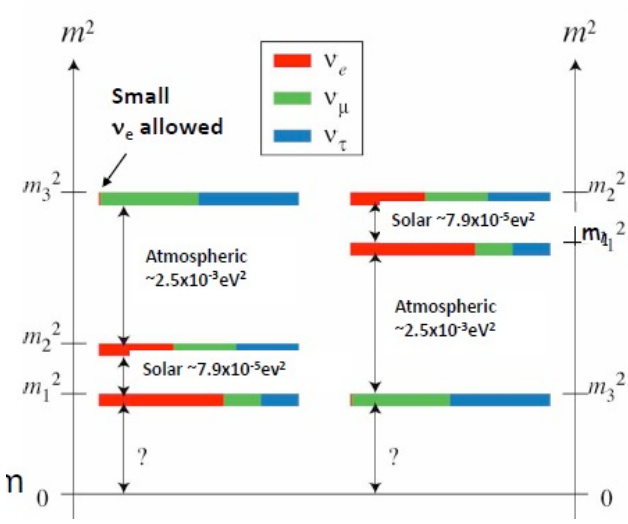

Figure ?? Placeholder for a better graphic

3.4.3 Measuring θ_{13}

[This section introduces the present generation of experiments trying to measure theta13. Very brief description of the reactor searches. Brief description and status of T2K and NOvA. Include "predictions" for size of theta13. Conclusion that LBNE will assume that sin22theta13 is 0.01 or larger.]

3.4.4 Measuring ν_e appearance in LBNE

[In this section, we show the plot of numu2nue probability versus energy for a 1,300-km baseline. We briefly discuss why this is a good choice of baseline. We briefly summarize the characteristics of the neutrino beam and include the reference design spectrum. We include a detailed table of event rates in units of nu/kT/10^20 POT (detector independent-perfect efficiency); use values of sin22theta13 of 0.1(?) and 0.01(?) as extreme limits for the signal. Includes event rates for numu (non oscillated and oscillated), intrinsic and solar nues.]

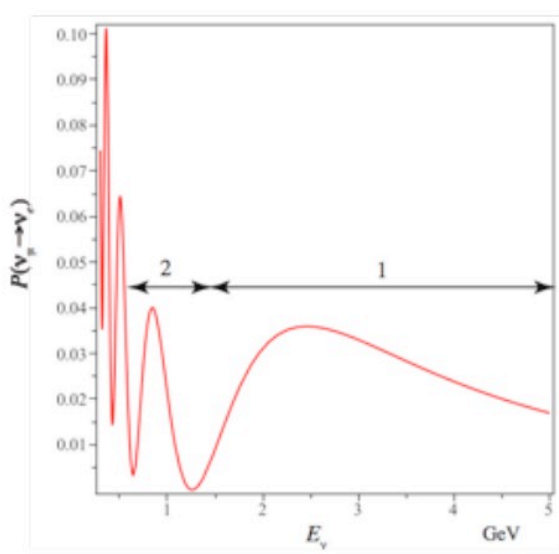

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Figure ?? Oscillation probability versus neutrino energy for a 1,290-km baseline

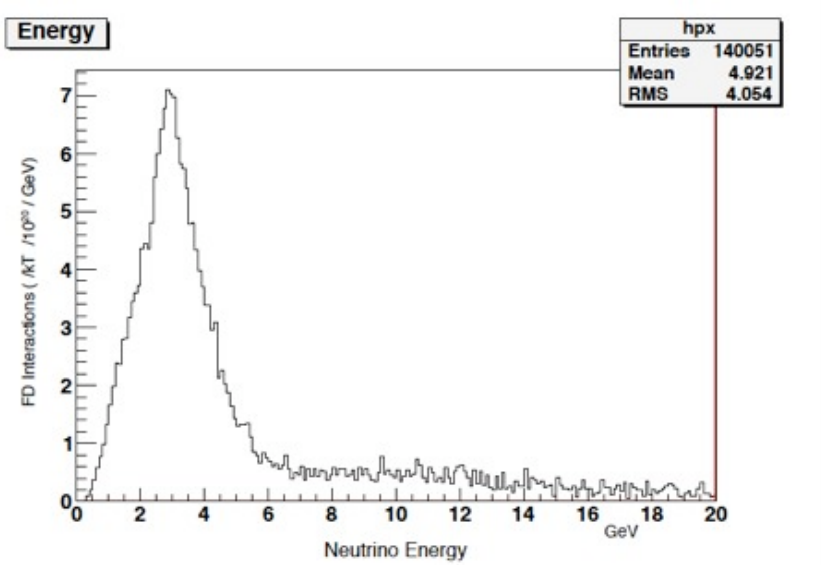

Figure ?? : Far detector interactions versus neutrino energy. [Placeholder until we get a final spectrum] The number of charged-current interactions in the absence of oscillations is shown for the reference design. As seen in Fig.?? (above), the significant energy regime for the physics is for energies below 6 GeV. The signal events are a product of this spectrum and the probability of Fig ?? (above).

3.4.5 Sensitivity Reach in LBNE

3.4.5.1 θ_{13}, Mass Hierarchy and δ_{CP}

[In this section, we describe how the sensitivity calculations for theta13, mh and CP are done. We present an analysis for a perfect detector, i.e. perfect ne efficiency and background only from the intrinsic ne in the beam. This analysis determines the perfect detector mass needed to achieve a desired sensitivity for each of the measurements.

The concepts of detector efficiency, background rejection and systematic errors are described. It tells the reader that the detector designs are what determine these numbers and that **what they are for LBNE are fully described in the respective volumes for each technology and the**

near detector.

Sensitivity plots presented in this section are using the parameters of the reference designs presented in the CDR. A table summarizing the performance characteristics of WC and LAr is included (these numbers are generated by the Physics Working Group or detector simulators). All sensitivities are calculated for a number of protons on target (not quoting a beam power).

This section includes a series of sensitivity plots that demonstrate that our reference design configurations are worth building.]

Figure ??

3.4.5.2 Precision Measurements (θ_{23}, Δm^2_{23})

[This section includes the discussion of the precision that can be made on these parameters.]

3.5 Search for Proton Decay

3.5.1 Theoretical Motivation

The possibility that the proton is unstable has intrigued physicists since the early 1970s. In the context of a unified picture of the fundamental particles (quarks and leptons) and interactions (strong, electromagnetic and weak), proton decay appears as a consequence Grand Unification Theories (GUTS). It is strongly supported by the meeting of the strengths of the three forces that are predicted to occur at high energies (~10^{16} GeV) in the context of super symmetry. One of the most crucial predictions of Grand Unification is that the proton must ultimately decay into a lepton and a meson, revealing quark-lepton unity.

The theoretical guidance provided by some promising models points toward the need for improved searches for a proton decaying into $\bar{\nu}K^+$ and $e^+\pi^0$ modes with lifetimes less than about 2×10^{34} and 10^{35} years respectively.

3.5.2 Experimental Searches

[Brief summary of 1st and 2nd generation searches; summary table of present limits for decay modes searched for (need to find the reference); highlight current limits on the favored modes..]

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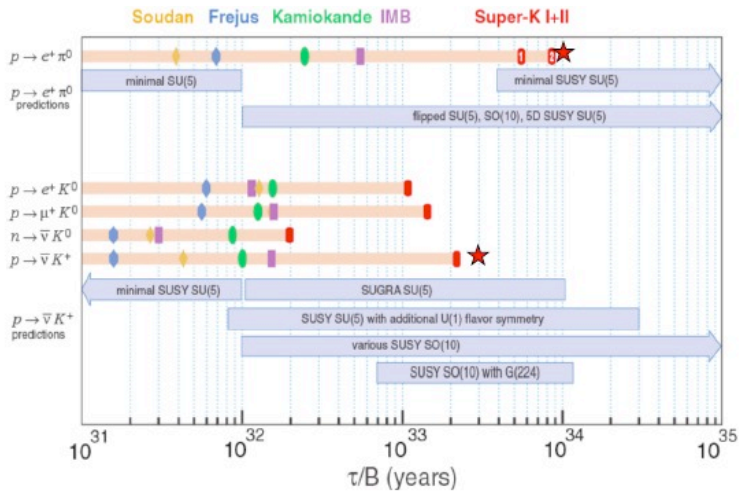

Figure ?? – Reference

3.5.3 Search with LBNE Detectors

In the following sections, we present the capability of the proposed LBNE detectors to extend the search for proton decay by an order of magnitude or more over the current limits.

3.5.3.1 Water Cherenkov Detector

Text goes here…

3.5.3.2 Liquid Argon Detector

Text goes here…

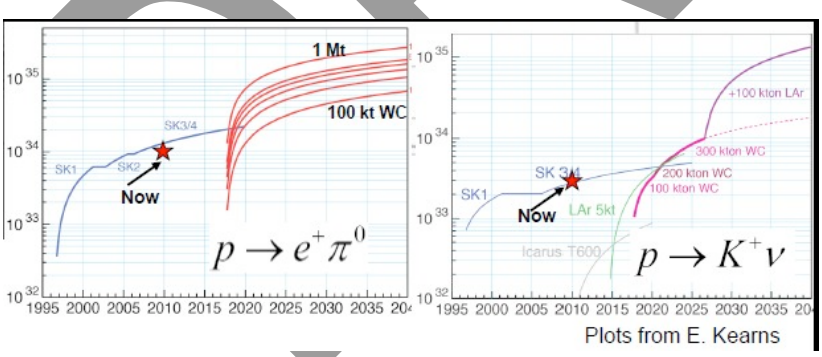

Figure ?? – placeholder; needs to be done based on potential LBNE configurations

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3.6 Galactic Supernova Bursts

3.6.1 Introduction

A core-collapse supernova releases about 99% of its energy in an initial neutrino burst that lasts a few tens of seconds, expelling about half the neutrinos in the first second. Due to the small neutrino cross section, we can only detect these massive neutrino bursts from supernovae in our own galaxy or nearby galaxies. Supernova neutrino energies range in the few tens of MeV, and their luminosity is divided more-or-less equally among the three neutrino flavors. The following science topics could be addressed by observing a high-statistics core-collapse neutrino signal:

- The properties of neutrinos
- The astrophysics of core collapse
- The supernova progenitor

[Text for each of these exists in the WP]

3.6.2 Historical Context

The observation of 19 neutrino events in two water Cherenkov detectors for SN1987A in the large Magellanic Cloud (55 kpc) confirmed the baseline model of core collapse, but left many questions unanswered. [Expand and references.]

3.6.3 Predictions

Scientists expect supernovae to occur within or nearby the Milky Way a few times per century. Those at a distance of 10 – 15 kpc have the highest probability of being detected. Within about one Mpc, the rate could be as high as one per year. A distribution of expected event rate versus distance is given in Reference [], and included as Figure []. From 10 kpc (the center of our galaxy), a core-collapse supernova would produce a few hundred neutrino interactions per kiloton of either a water Cherenkov or liquid argon detector. The expected number of events scales with distance as $1/D^2$.

3.6.4 Next Generation Detection

In the following sections, we describe the experimental signatures of supernova neutrinos in the detectors proposed for LBNE, namely water Cherenkov and liquid argon. These two technologies are highly complementary for the detection of supernova neutrinos. A water Cherenkov detector detects $\bar{\nu}_e$, while liquid argon detects mainly ν_e events. A combination of the two would allow important checks on our understanding of astrophysics as well as neutrino properties.

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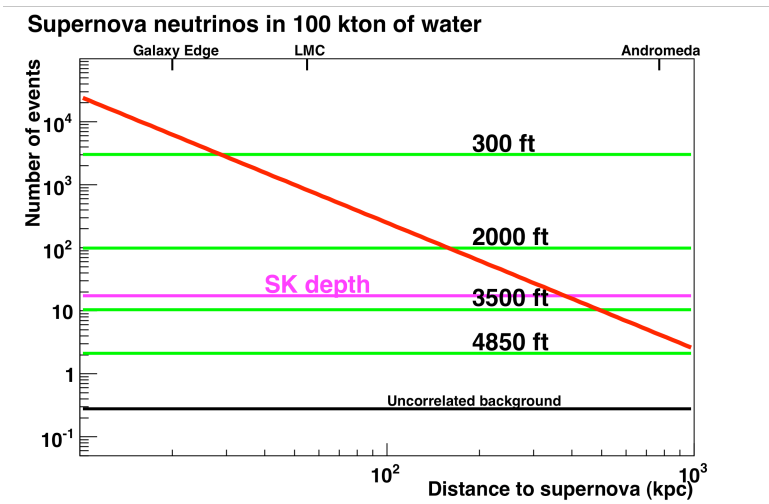

Figure ?? Update – take off the SuperK line ; highlight the LBNE depth(s)

3.6.4.1 Water Cherenkov Detector

In water, the dominant neutrino interaction is the inverse beta decay:

$$\bar{\nu}_e + \pi \rightarrow \varepsilon^+ + \nu \qquad \text{(Eq)}$$

There will also be some charged current (CC) interactions with oxygen in water:

$$\nu_e + {}^{16,18}O \rightarrow {}^{16,18}\Phi + \varepsilon^-$$
$$\bar{\nu}_e + {}^{16}O \rightarrow {}^{16}N + \varepsilon^+$$

A cascade of 5-10 MeV de-excitation γ's will also tag:

$$\nu_x + {}^{16}O \rightarrow \varpi_\xi {}^{12}O^*$$

Elastic scattering, $\nu_{e,x} + \varepsilon^- \rightarrow \varpi_{\varepsilon,\xi} + \varepsilon^-$, while representing only a few percent of the total signal due to its directional nature, will allow pointing to the supernova. Estimated event rates for the 10-kpc signal in a 100-kT detector are listed in Table 1. [Need to discuss detection efficiency and backgrounds.]

Process	No. of Interactions
$\bar{\nu}_e + \pi \rightarrow \varepsilon^+ + \nu$	23,000
$\nu_e + {}^{16,18}O \rightarrow {}^{16,18}\Phi + \varepsilon^-$	1,000
$\nu_x + {}^{16}O \rightarrow \varpi_\xi {}^{12}O^*$	1,100

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$\nu_{e,x} + \varepsilon^- \rightarrow \varpi_{\varepsilon,\xi} + \varepsilon^-$	1,000

Table XX

At the 4,850-ft depth, cosmic ray muon background during the burst should be small in a water detector, even without muon veto rejection. Un-vetoed background in water may come from radioactivity, flashing phototubes, remaining spallation events, or "invisible muons" from atmospheric neutrinos and solar neutrinos, however, these should be negligible in a short-burst time window.

3.6.5 Liquid Argon Detector

[Describe the detection mechanism, expected event rates (as a function of distance?) and backgrounds.]

3.7 Supernova Relic Neutrinos

3.7.1 Introduction

Core-collapse supernova explosions throughout the history of the universe left behind a diffuse background of neutrinos, which should be detectable on Earth. While these supernova relic neutrinos (SRN) undoubtedly suffuse the universe, they have thus far evaded detection. The flux and spectrum of these neutrinos contain information about the rate of supernova explosions (and consequently the star formation rate) in the past. Because the existence of such a flux is a robust prediction of most models of stellar formation, observation of this flux would provide a key indication that our general idea of how and in what epoch stars formed is correct.

To date, Super-Kamiokande has set the world's best limit on the flux of these particles. [Short summary of the results; probably table.]

This limit is tantalizingly close to the majority of modern theoretical predictions. Figure [] shows the existing limit on the flux of SRN from Super-Kamiokande and the predictions from several published models.

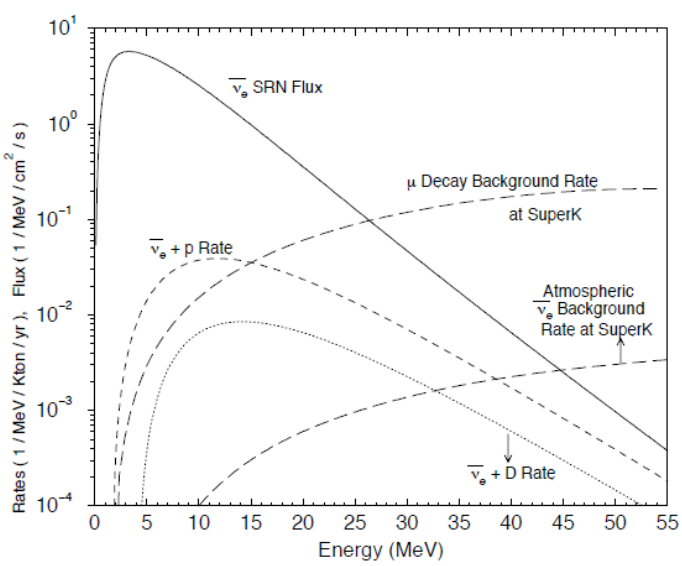

Figure []

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Though SRN models vary, according to one widely accepted modern analysis [ref], a 300-kT water Cherenkov detector located deep underground and doped with gadolinium should record about 50 of these supernova events every year. This data would undoubtedly stimulate new theoretical (and perhaps even experimental) developments in the neutrino and cosmology communities.

3.7.2 Detection Requirements and Capability

3.7.2.1 Water Cherenkov Detector

The best signal of supernova relic neutrinos in a water Cherenkov detector is the positrons resulting from the inverse beta reaction (Eq). While the maximum flux occurs at energies below 5 MeV, 10 MeV marks the practical lower limit for detecting positrons from this interaction. This is above the background from reactors (~10 MeV) and well below the atmosphere antineutrino background (~100 MeV). Above ~20 MeV, the dominant background is due to the decay of sub-Cherenkov threshold muons from atmospheric neutrino interactions. This background could be greatly reduced by tagging the neutron that accompanies each inverse beta reaction by observing the γ rays associated with its capture.

[Description of Gd doping gains.]

[For a water Cherenkov detector, we estimate a possible positron energy threshold of 15.5 MeV. For a 300-kT detector located at a depth of 4,850 ft, this will yield a 90% CL sensitivity for the relic neutrino flux of < 0.3 cm-2sec-1, below the predictions in []. This analysis needs to be updated for LBNE detectors constructed in one or two 100-kT modules.]

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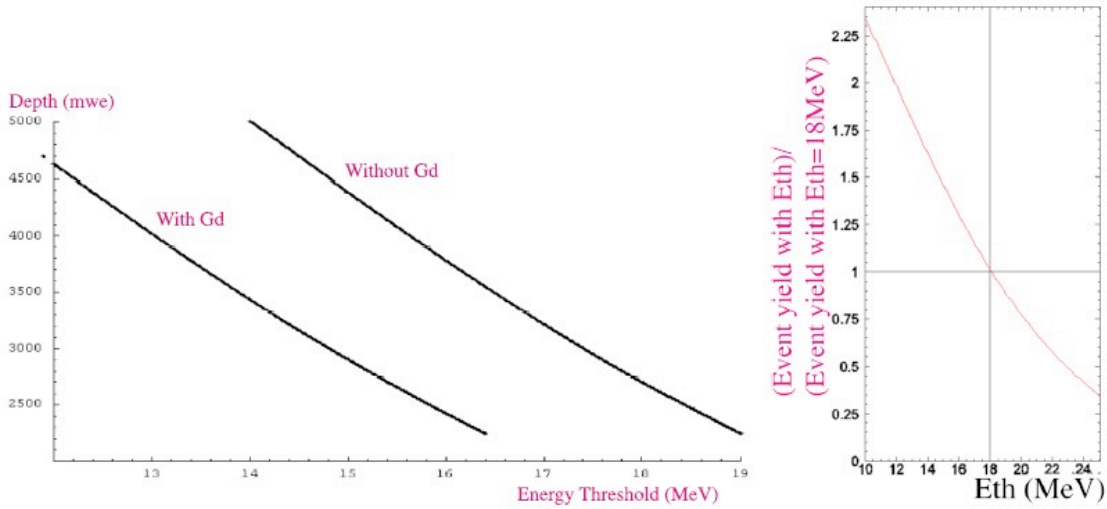

Figure []

3.7.2.2 Liquid Argon Detector

Supernova relic neutrinos and antineutrinos will interact in liquid argon detectors via both charged and neutral current interactions.

3.8 Short-baseline Physics

[In this section, we discuss the requirements of the near detector to provide the data necessary for the beam oscillation measurements. We summarize the reference design being presented in Volume 3. We give a brief summary of the additional measurements that could be made with the reference Near Detectors.]

3.9 Additional Physics Opportunities

[The discussion in these sections will depend on the contributions from the Physics Working Groups in these topical areas. Each group should contribute a discussion of the motivation for the measurements and then present the capability to make measurements given the LBNE Project reference detectors. Discussion of results achievable with a different (more desirable, i.e. larger) detector can also be submitted and will be included with the appropriate caveats.]

3.9.1 Atmospheric Neutrinos

Text goes here…

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3.9.2 Solar Neutrinos

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3.9.3 Geoneutrinos and Reactor Neutrinos

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3.9.4 Ultra High Energy Neutrinos

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