The CAPTAIN Detector and Physics Program

September 9, 2013

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# Contents

1 Introduction ................................. 1

2 The CAPTAIN Detector .................... 4
   2.1 Cryostats ................................ 5
   2.2 Cryogenics ............................... 6
   2.3 Electronics ............................... 7
   2.4 TPC ..................................... 7
      2.4.1 CAPTAIN TPC ......................... 7
      2.4.2 Prototype TPC ......................... 9
   2.5 Photon Detection System ................. 9
   2.6 Laser Calibration System ............... 10
   2.7 Special Run Modes ....................... 11
      2.7.1 Tests of Doping Liquid Argon to Improve Light Output 11

3 Neutrons .................................. 12
   3.1 Physics Importance ....................... 12
   3.2 High-intensity neutron running .......... 14
   3.3 Low-intensity neutron running .......... 15
      3.3.1 Low-energy neutron run ............. 15
      3.3.2 High-energy neutron run ............. 15
   3.4 Run Plans ............................... 16

4 Neutrinos .................................. 17
   4.1 Running at NuMI ......................... 17
      4.1.1 On-axis running in NuMI .......... 17
      4.1.2 Off-axis running in NuMI .......... 20
   4.2 Running at the SNS ....................... 20
   4.3 Stopped Pion Source at the BNB .......... 23
   4.4 Other Neutrino Possibilities .......... 24

5 Conclusions .............................. 25
Abstract

The Cryogenic Apparatus for Precision Tests of Argon Interactions with Neutrino (CAPTAIN) program is designed to make measurements of scientific importance to long-baseline neutrino physics and physics topics that will be explored by large underground detectors. CAPTAIN began as part of a Los Alamos National Laboratory (LANL) Laboratory Directed Research and Development (LDRD) project and has evolved into a multi-institutional collaboration. The program employs two detectors. The CAPTAIN detector is a liquid argon TPC deployed in a portable and evacuable cryostat that can hold a total of 7700 liters of liquid argon. Five tons of liquid argon are instrumented with a 2,000 channel liquid argon TPC and a photon detection system. The cryostat has ports that can hold optical windows for laser calibration and windows for the introduction of charged particle beams. The materials for the detector are currently being acquired. Assembly is anticipated to begin August of 2013, with a commissioning period ending in the summer of 2014. During commissioning, laser calibration and cosmic-ray data will be taken and analyzed. Subsequent to the commissioning phase, the detector will be moved to a high-energy neutron beamline that is part of the Los Alamos Neutron Science Center. The neutron data will be used to measure cross-sections of spallation products that are backgrounds to measurements of neutrinos from a supernova burst and cross-sections of events that mimic the electron neutrino appearance signal in long-baseline neutrino physics. The data will also be used to develop strategies for counting neutrons and evaluating their energies in a liquid argon TPC that are important for the total neutrino energy measurement in the analysis of long-baseine neutrinos. The prototype detector is being fabricated in a cryostat supplied by the University of California at Los Angeles (UCLA) group and consists of a 1,000 channel liquid argon time-projection chamber (TPC). Fabrication also begins in August of 2013, but will be completed more quickly than the CAPTAIN detector. The prototype detector will allow an end-to-end test of all components in time to make adjustments to the scheme employed by CAPTAIN. The prototype will collect cosmic-ray and laser calibration data earlier than will be possible in CAPTAIN allowing the development of analysis techniques at an earlier date. Finally, the prototype will allow for testing of calibration and other ideas in parallel to the running of CAPTAIN.

Subsequent to the neutron running, the CAPTAIN detector will be moved to a neutrino source. There are several possible neutrino sources of interest. The two most likely neutrino possibilities are an on-axis run in the NuMI (Neutrinos at the Main Injector) beamline at Fermi National Accelerator Laboratory (FNAL) and a run in the neutrino source produced by the Spallation Neutron Source (SNS) at Oak Ridge National Laboratory. An on-axis run at NUMI produces more than one million events of interest in a two or three year run at neutrino energies between 1 and 10 GeV. The neutrino studies are complementary to the MicroBooNE experiment, which will measure similar interactions at a lower, complementary energy range - 0.5 to 2 GeV. Many important exclusive and inclusive charged and neutral current channels can be measured by such a run. In addition, a detailed evaluation of
strategies to measure the total neutrino energy including neutrons emitted by the argon nucleus are made possible by this run. The SNS produces a neutrino source as a byproduct of its neutron production. The neutrinos result from the decays stopped positively charged pions and muons. The neutrino energy spectrum produced from these decays is a broad spectrum up to 50 MeV. If located close to the spallation target, CAPTAIN can detect several thousand events per year in the same neutrino energy regime where neutrinos from a supernova burst are. Measurements at the SNS yield a first measurement of the cross-section of neutrinos on argon in this important energy regime. In addition, this would be the first measurement of low-energy neutrinos in a liquid argon TPC. This is critical for the interpretation of a supernova burst in the LBNE far detector and will greatly affect the specifications for the light collection and DAQ systems.
Chapter 1

Introduction

The development of the CAPTAIN (Cryogenic Apparatus for Precision Tests of Argon Interactions with Neutrinos) experiment began as a part of an Los Alamos National Laboratory (LANL) Laboratory Directed Research and Development (LDRD) project. The three-year LDRD project is designed to enhance the science associated with the Long-Baseline Neutrino Experiment (LBNE). The project involves scientists from three groups in two divisions engaged in an integrated effort of theory, simulation and detector work. CAPTAIN is the major hardware effort of the LDRD project and involves significant contributions from the entire experimental and technical staff supported by the project.

From the early stages of development, the LANL team received significant technical assistance from Brookhaven National Laboratory (BNL), Fermi National Accelerator Laboratory (FNAL), and the University of California at Los Angeles (UCLA). In additional to technical assistance, the UCLA group has provided a cryostat that will contain the CAPTAIN prototype detector.

The scientific focus of the CAPTAIN program is to make measurements important for the development of the Long-Baseline Neutrino Experiment (LBNE). LBNE is a broad scientific program being developed in the United States as an international partnership. It consists of an intense neutrino beam produced at FNAL, a highly capable set of neutrino detectors on the FNAL campus, and a large underground liquid argon time projection chamber (TPC) at Sanford Underground Research Facility (SURF), giving a 1300 km oscillation baseline. The high-intensity neutrino beam will allow high precision measurements of neutrino and anti-neutrino mixing separately. enabling detailed studies of neutrino oscillations, including measurements of the mass hierarchy, CP violation, and non-standard neutrino interactions (NSI). In addition to serving as a far detector for the long-baseline neutrino physics program, the large underground far detector enables a broad scientific program that includes searches for nucleon decay mediated by beyond the standard model physics, the study of neutrinos from galactic supernova bursts, indirect searches for the annihilation products of dark matter particles and the detailed study of atmospheric neutrinos. The CAPTAIN program impacts several of the topics that make up the LBNE physics program via two prongs of study: low energy neutrino physics and medium energy neutrino physics.

The primary low-energy neutrino signal in LBNE will be from charged-current (CC)
electron neutrinos.

\[ \nu_e + {}^{40}\text{Ar} \rightarrow e^- + {}^{40}\text{K}^* \]  

(1.1)

The transition to the ground state of potassium is forbidden, so in general, the CC electron neutrino signal is accompanied by one or more de-excitation gamma-rays. The cross-section has never been measured and has theoretical uncertainties in the range of 10 to 15 percent. Backgrounds to detecting this process in the LBNE far detector are from cosmic ray muon induced spallation processes. In addition, the final states consist of a single electron and a “halo” of gammas, making triggering and analysis challenging. The three most important spallation processes are the photonuclear interaction between the muon and an argon nucleus, neutron induced spallation of the argon nucleus and charged pion spallation of the argon nucleus. In the latter two processes, the neutrons and pions are produced by muon interactions in the rock surrounding the detector or in the detector itself. CAPTAIN will provide several important inputs for LBNE. First, CAPTAIN will measure neutron spallation processes in a high-energy neutron beam at the Los Alamos Neutron Science Center (LANSCE). Next, CAPTAIN will measure CC and neutral current (NC) low-energy neutrino cross-sections with a stopped-pion neutrino source at the Spallation Neutrino Source (SNS) at Oak Ridge National Laboratory (ORNL). The measurements will be the first low-energy neutrino measurements in a liquid argon TPC, and will provide practical inputs to the design of the LBNE far detector light collection and DAQ system.

Medium-energy neutrino interactions are poorly understood on any nucleus. There is a dearth of neutrino-argon data in the 1 to 10 GeV neutrino energy regime. LBNE will use data in this energy regime to make high-precision measurements of neutrino oscillation phenomena. Irrespective of the source of medium-energy neutrinos - beam or atmospheric -, neutrino oscillation studies depend on having well-constrained determinations of three quantities for each neutrino event: the neutrino flavor, the distance from the point of production, and the neutrino energy. In general, CC neutrino interactions in this energy regime will result in a lepton, the emission of several hadrons and a residual nucleus. While charged hadrons will be well-identified and measured, neutrons are harder to measure. They travel some distance from the neutrino interaction vertex and deposit energy via elastic and inelastic collisions with argon nuclei. The determination of the neutrino energy is therefore a significant challenge and possible systematic limitation to the LBNE neutrino physics program. CAPTAIN will address issues associated with neutrino energy reconstruction. First, CAPTAIN will make a detailed study of neutron interactions with argon as a function of neutron energy up to neutron kinetic energies of 800 MeV. Using these data, the collaboration will develop methodologies to constrain the neutron energy in a neutrino interaction. Next, with an on-axis NuMI run, where the neutrino beam is measured with a variety of detectors, CAPTAIN will make a detailed study of neutrino interactions on argon. The methodologies developed with the neutron data will be put to the test with the high statistics neutrino data. In addition, CAPTAIN will contain a large fraction of the hadronic component of the interactions, so the data will be an important test-bed for developing automated liquid argon reconstruction techniques critical for LBNE.

In the next chapter, we describe the CAPTAIN detector in detail. Subsequent chapters
are dedicated to a more detailed description of the CAPTAIN physics program.
The CAPTAIN Detector

The CAPTAIN program employs two detectors, a prototype detector, mini-CAPTAIN, and the full CAPTAIN detector. The design differences are driven by the cryostat sizes and geometries. The prototype is smaller and does not have side ports for windows. The CAPTAIN detector (Fig. 2.1) is a liquid argon time-projection chamber (TPC) deployed in a portable and evacuable cryostat that can hold a total of 7700 liters of liquid argon. Five tons of liquid argon are instrumented with a 2,000 channel TPC and a photon detection system. The cryostat has ports that can hold optical windows for laser calibration and windows for the introduction of charged particle beams.

The hardware subsystems consist of Cryostats, Cryogenics, Electronics, TPCs, Photon Detection System and Laser Calibration System. Below, we describe each subsystem in detail.
2.1 Cryostats

The CAPTAIN project utilizes two cryostats for TPC development. The first is a small, 1700L vacuum jacketed cryostat provided by UCLA for the effort. It is being modified at LANL to provide features to accommodate and test mini-CAPTAIN. The vacuum jacket is 60.25 inches in diameter, and the vessel is 64.4 inches in height.

The primary CAPTAIN cryostat is a 7700L vacuum insulated liquid argon cryostat which will house the final TPC. It is an ASME Section VIII, Division 1 U stamped vessel making operation at several national (or international) laboratories more straightforward. The outer shell of the cryostat is 107.5 inches in diameter, and it is 115 inches tall. The vessel is designed with a thin (3/16 inch) inner vessel to minimize heat leak to the argon. All instrumentation and cryogenics are made through the vessel top head. The vessel also has side ports allowing optical access to the liquid argon volume for the laser calibration system or other instrumentation. A work deck is to be mounted on the top head to provide safe worker access to the top ports of the cryostat. A baffle assembly will be included in the cold gas above the liquid argon to mitigate radiation heat transfer from the un-insulated top head. Figure 2.1 shows a schematic of the CAPTAIN cryostat, TPC, and work deck.
2.2 Cryogenics

Liquid argon (LAr) serves as target and detection medium for the CAPTAIN detector. The argon must stay in the form of a stable liquid and must remain minimally contaminated by impurities such as oxygen and water. This is to prevent the loss of drifting electrons to these electronegative molecules. It must also stay sufficiently free of contaminants such as nitrogen to avoid absorption of the scintillation light.

The maximum drift distance is 100.0 cm for the full CAPTAIN detector and 32.0 cm for the prototype. To achieve a sufficiently long drift-distance for electrons, the O\textsubscript{2} contamination is required to be smaller than 750 ppt for mini-CAPTAIN and 240 ppt for CAPTAIN. The purity received at Los Alamos from industry has an oxygen level of not more than 2.3 ppm. Quenching and absorption of scintillation light are demonstrated [1, 2] to be negligible when the N\textsubscript{2} contamination is smaller than 2 ppm.

The cryogenics system must receive liquid argon from a commercial vendor, test its purity, and further purify it. Figure 2.2 shows the basic design. Cryogenic pumps and filter vessels purify the liquid in the detector by removing electronegative contaminants. Cryogenic controls monitor and regulate the state of the argon in the detector. Commercial analytic instruments are used to characterize the oxygen and water contaminant levels in the argon. The CAPTAIN liquid argon delivery and purification design is based on experiences of the MicroBooNE experiment [3] and the Liquid Argon Purity Demonstration (LAPD) [4], both based at Fermilab.

![Figure 2.2: The design of purification system [3] [4].](image)

The CAPTAIN TPC has a liquid argon volume of 7.5 m\textsuperscript{3}, this is equivalent to 6300 m\textsuperscript{3} of argon gas at STP. Assuming a bulk liquid argon contamination level of O\textsubscript{2} with a 1.0 ppm, this is equivalent to 8.253 grams of O\textsubscript{2} in the total volume of the detector. The current design
for the vessel that will hold the two filter mediums has a total volume of \(\sim 80.0\) liters, or \(\sim 40.0\) liters for each filter material. The dual filter system consists of a bed of molecular sieve (208604-5KG Type 4A) to remove moisture and another bed of activated copper material (CU-0226 S 14 X 28) to remove oxygen. Experience from LAPD shows this should be sufficient. Both of these filter materials can be reactivated, after reaching saturation, by flowing a mixture of argon gas with 2.5% hydrogen gas at an elevated temperature.

The design utilizes a 10-12 gal/min capacity commercial centrifugal pump. Magnetic coupling prevents contamination through shaft seals. The pump will be mounted with the filter vessel on a single skid in order to achieve portability.

A sintered metal filter is used to remove dust from the liquid argon prior to its delivery to the cryovessel.

### 2.3 Electronics

The electronic components for the TPC are identical to those of the MicroBooNE experiment at FNAL [3]. A block diagram of the electronics is in Figure 2.3. The front-end mother board is designed with twelve custom CMOS Application Specific Integrated Circuits (ASIC). Each ASIC reads-out 16 channels from the TPC. The mother board is mounted directly on the TPC wire planes and is designed to be operated in liquid argon. The output signals from the mother board are transmitted through the cold cables to the cryostat feed-thru to the intermediate amplifier board. The intermediate amplifier is designed to drive the differential signals through long cable lengths to the 64 channel receiver ADC board. The digital signal is then processed in an FPGA on the Front End Module (FEM) board. All signals are transmitted via fiber optic from a transmit module to the data acquisition computer.

![Figure 2.3: The MicroBooNE electronics chain to be used for CAPTAIN [3].](image)

### 2.4 TPC

#### 2.4.1 CAPTAIN TPC

The TPC consists of a field cage in a hexagonal shape with a mesh cathode plane on the bottom of the hexagon and a series of four wire planes on the top with a mesh ground plane. The apothem of the TPC is 100 cm and the drift length between the anode and cathode is
100 cm. In the direction of the electron drift, there are four wire planes. In order, they are the a grid, U, V, and collection (anode) plane. The construction material of the TPC is FR4 glass fiber composite. All wire planes have 75 $\mu$m diameter copper beryllium wire spaced 3 mm apart and the plane separation is 3.125 mm. Each wire plane has 667 wires. The U and V planes detect the induced signal when the electron passes through the wires. The U and V wires are oriented $\pm 60$ degrees with respect to the anode wires. The anode wires measure the coordinate in direction of the track and U and V are orthogonal to the track. The third coordinate is determined by the drift time to the anode plane.

The field cage is realized in two modules: the drift cage module, and the wire plane module. The wire plane module incorporates a 2.54 cm thick FR4 structural component that supports the load of the four wire planes so that the wire tension is maintained. The field cage is double sided gold plated copper clad FR4 arranged with 5 mm wide traces separated by 1 cm. A resistive divider chain provides the voltage for each trace. The design voltage gradient on the divider chain is 500 V/cm when 50 kV is applied to the cathode. The electrons from the ionized event are collected on the anode plane. The U, or V planes detect signals via induction, and are made transparent to electrons via biasing. The drift velocity of the electrons with 500 V/cm is 1.6 $mm/\mu s$. See Figure 2.4

![Component detailed view of the CAPTAIN TPC.](image-url)
2.4.2 Prototype TPC

The prototype TPC is a smaller version of the CAPTAIN TPC. The drift length is 32 cm and the apothem is 50 cm. Each wire plane has 337 wires. The prototype is designed to test the mechanical construction details of the TPC, the cold electronics, and the back-end data acquisition system prior to the construction of the full scale CAPTAIN. It also allows the early development of the data acquisition software so that CAPTAIN can produce data as soon as the hardware is ready. It will also provide the needed operational experience to run the full scale CAPTAIN.

2.5 Photon Detection System

By detecting the scintillation light produced during interactions in the CAPTAIN detector, the photon detection system provides valuable information. Simulations show that detection of several photoelectrons per MeV for a minimum ionizing particle (MIP) in a TPC with a field of 500 V/cm improves the projected energy resolution of the detector by 10-20%. Such improvement stems from the anti-correlation between the production of scintillation photons and ionization electrons, a phenomenon which has been conclusively observed to improve calorimetry already in liquid xenon [5]. Hints of it have already been seen in our own re-analysis of older liquid argon data that included simultaneous measurements of light and charge yields at the same electric fields [6]. If confirmed by CAPTAIN, it will increase the utility of the photon detection systems of other experiments such as LBNE, as well as argon-based dark matter detectors. Just as with the charge signal, the amount of light produced by a particle traversing argon is a function of the energy deposited. The scintillation light can also be used to determine the energy of neutrons from time of flight when the experiment is placed in a neutron beamline by giving the time of the interaction with few nanosecond resolution.

Liquid argon scintillates at a wavelength of 128 nm which unfortunately is readily absorbed by most photodetector window materials. It is thus necessary to shift the light to the visible. The photon detection system is composed of a wavelength shifter covering a large area of the detector and a number of photodetectors to collect the visible light. The baseline CAPTAIN photon detection system uses tetraphenyl butadiene (TPB) as a wavelength shifter and sixteen Hamamatsu R8520-500 photomultiplier tubes (PMT) for light detection. The R8520 is a compact PMT approximately 1” x 1” x 1” in size with a borosilicate glass window and a special bialkali photocathode capable of operation at liquid argon temperatures (87 K). It has a 25% quantum efficiency at 340 nm. TPB is the most commonly used wavelength shifter for liquid argon detectors and has a conversion efficiency of about 120% when evaporated in a thin film. It has a re-emission spectrum that peaks at about 420 nm [7]. The TPB will be coated on a thin piece of acrylic in front of the PMTs. Eight PMTs will be located on top of the TPC volume and eight on the bottom. This will provide a minimum detection of 2.2 photoelectrons per MeV for a MIP. The amount detected will increase if the entire top and bottom surfaces are coated with TPB.
The PMTs will use a base with cryogenically compatible discrete components. The cable from the base to the cryostat feedthrough is Gore CXN 3598 with a 0.045” diameter to reduce the overall heat load. The PMT signals will be digitized at 250 MHz using two 8-channel CAEN V1720 boards. The digitizers are readout through fiber optic cables by a data acquisition system written for the MiniCLEAN experiment [8].

The CAPTAIN detector will serve as a test platform for the evaluation of alternative photon detection system designs. The design will allow testing options in a operating TPC with cosmic muons and in various beamlines. Such options include other wavelength shifting films, acrylic light guides or doped panels to the photodetectors, and other types of photodetectors such as SiPMTs, larger cryogenic PMTs, and avalanche photodiode arrays. In addition, CAPTAIN can test methods of calibrating the photon detection system with the laser calibration system or alternatively a series of UV and blue LEDs.

2.6 Laser Calibration System

The first measurement of photoionization of liquid Argon was performed by Sun et al. [9]. Using frequency quadrupled Nd-YAG laser to generate 266nm light the authors demonstrated that the ionization was proportional to the square of the laser intensity. The ionization potential of liquid Argon is 13.78 eV, slightly lower than the energy of 3 photons from a 266nm quadrupled Nd-YAG laser. The ability to create well-defined ionization tracks within a liquid Argon TPC provides an excellent calibration source that can be used to measure the electron lifetime in-situ and to determine the drift field within the TPC itself. Significant progress has been made in this field and is documented in Rossi et al. [10]. The CAPTAIN TPC provides an excellent test bed for a future LBNE laser calibration system.

| Wavelength | 1064 nm | 532 | 266 |
|------------|---------|-----|-----|
| Pulse Energy | 850 mJ | 400 mJ | 90 mJ |
| Pulse Duration | 6 ns | 4.3 ns | 3 ns |
| Peak Power | 133 MW | 87 MW | 28 MW |
| Peak Intensity | 1500 GW/cm² | 985 GW/cm² | 317 GW/cm² |
| Photon Energy | 1.17 eV | 2.33 eV | 4.66 eV |
| Photon Flux | $8 \times 10^{30} \gamma/(s - cm²)$ | $2.6 \times 10^{30} \gamma/(s - cm²)$ | $0.42 \times 10^{30} \gamma/(s - cm²)$ |

To avoid surface irregularities that may disperse the laser beam the CAPTAIN TPC will employ optical access on the sides of the detector (Fig. 2.1). A LANL existing Quantel Brilliant B Nd-YAG laser will be used to ionize the liquid Argon. The laser parameters are given in Table 1. The laser and mirrors are in hand and the design of the mirror mounting system on the TPC frame has begun. The design seeks to be flexible and allow several paths through the liquid Argon, including parallel and at an angle to the wire plane. This will allow us to determine the electron lifetime within the CAPTAIN TPC.
2.7 Special Run Modes

2.7.1 Tests of Doping Liquid Argon to Improve Light Output

Previous research [11, 12, 13] suggests that there is a potential benefit to doping liquid argon with xenon or other wavelength shifting compounds to improve the collection of photons in a LAr TPC with little effect on the ionization readout. The possible advantages would be to shorten the triplet state lifetime for the scintillation photons from 1.6 microseconds and possibly shift the scintillation light from 128 nm to 178 nm (for xenon) or higher (for other compounds). A shift in scintillation light wavelength would have a large impact since the Rayleigh scattering length is proportional to $1/\lambda^4$ resulting in less scattering and better time resolution in a large detector. Higher wavelength scintillation light would also open up the possible use of other photodetectors and remove the need for wavelength shifting coatings such as TPB. CAPTAIN would serve as an ideal detector to study how much xenon or dopant would be needed to speed up the triplet lifetime. The literature has studied a broad range of levels from several ppm to $\sim$1% but only in small detectors with a poor ability to determine the final mixture. How the xenon or dopant remains in the LAr over time could be examined along with the ability to achieve uniform mixing in a large detector. With the TPC, the affect of concentration on the drift velocity and electrostatic properties would be examined. Finally, the best method for introducing the xenon or dopant could be developed.
Chapter 3

Neutrons

3.1 Physics Importance

A detailed understanding of neutron interactions with argon is crucial for the success of LBNE. They impact two major LBNE missions: low-energy neutrino detection - important for supernova neutrino studies, and neutrino oscillation studies with medium-energy neutrinos.

In the first case, neutron spallation on argon nuclei is an important channel for the production of isotopes that comprise the background to the detection of low-energy neutrinos - for example, those from supernova bursts. Studying neutron spallation of the argon nucleus with a well-characterized neutron beam is therefore compelling. Additionally, the neutral-current interactions of supernovae neutrinos on argon nuclei will leave them in excited states. This interaction can be well-simulated by bombarding argon with fast neutrons. The detection and identification of de-excitation events following neutron-argon interactions is an important step in establishing whether or not neutral-current interactions of supernovae neutrinos are detectable in a LAr TPC.

In the second case, neutrons are an important component of the hadronic system in medium-energy neutrino interactions with argon. Charged hadrons are well-measured and neutral pions will decay quickly into gamma-rays that point back to the neutrino vertex. Neutrons, on the other hand, will travel some distance from the neutrino vertex before interacting and will complicate the reconstruction of these events. Besides this, the study of neutron-induced pion production and spallation events in LAr in terms of their topology, of the multiplicity and identity of the visible particles in the final state and of their kinematic properties, is important for LBNE because similar events will be produced by neutrino and antineutrino interactions. Additionally, at the near site, neutrons will comprise an important in-time background to neutrino detection. Measuring neutron interactions as a function of neutron energy up to relatively high kinetic energies is thus important. With these topics in mind, we have developed a neutron running program with CAPTAIN in addition to measurements at neutrino beams. Such measurements have not been previously performed
For few GeV neutrinos (antineutrinos) delta production is the principle source of pion production. In neutral current interactions only $\Delta^+$ and $\Delta^0$ will be produced. However the neutrino cross section is larger by a factor of $\sim 2$ because of differing interference effects due to the opposite helicity of neutrinos and antineutrinos. The final charge state of the pions produced in neutral current interactions is important for identifying the relative neutrino and antineutrino flux. Pions are readily absorbed and can change their charge state via final state interactions, so it is also important to characterize the final state interactions in argon. Figure 3.1 left (reproduced from [14]) shows the cross-section for pion production from 450 MeV neutrons at various angles from different nuclei scaled by $A^{2/3}$. The upper 5 distributions are for $\pi^-$ while the one at the bottom is for $\pi^+$. The large dominance of $\pi^-$ over $\pi^+$ might be surprising but is qualitatively understandable if one considers pion production as proceeding via delta production as shown in Figure 3.1 right. The figure on the right illustrates the asymmetry in pion production by neutrons on a N=Z nucleus via the delta resonance. In reality, the observed ratio $\pi^-/\pi^+$ is always less than 11 indicating the importance of the role played by final state interactions. It will be important to separate the pions coming from deltas formed in the nucleus from those formed on the incident neutron as the former better reflect the deltas formed via neutrinos (antineutrinos).

The CAPTAIN program takes advantage of the proximity of the Los Alamos Neutron Science Center (LANSCE) to the CAPTAIN commissioning hall. LANSCE has a beamline with a well-characterized neutron energy spectrum with an endpoint close to 800 MeV kinetic energy (Figure 3.2). The energy of the incoming neutrons can be determined on an event-by-event basis by measuring their time of flight.

It is worth noting, while the goal for LBNE is to install the far detector deep underground, the current approved scope for LBNE has the far detector on the surface. For surface operations, collection and analysis of neutron data are absolutely critical. First, at the
surface, there is a significant cosmic-ray neutron flux that will impinge on the detector. The spectrum shown in Figure 3.2 is quite similar to the cosmic-ray spectrum, but much more intense. With a few days of running, we will measure the neutron production of isotopes such as $^{40}$Cl that constitute an important background to supernova neutrino detection. Surface running also presents a challenge to the long-baseline neutrino program. High-energy cosmogenically produced neutrons can produce events with neutral pions that can mimic the electron neutrino appearance signal for LBNE. Currently, simulations show that 10% of the electron neutrino appearance background could come from fast neutrons with complicated FSI, but uncertainties are large and must be measured prior to finalizing surface shielding requirements and photon system specifications.

In the following we briefly describe the measurements that we plan to perform using CAPTAIN in the LANSCE neutron beam.

### 3.2 High-intensity neutron running

The neutron flux shown in Figure 3.2 is much more intense than that produced by cosmic-ray interactions at the LBNE far detector site, so a single day of running will produce years worth of neutron spallation events in CAPTAIN. We will run in an integrated mode where we expose the detector to the full intensity of the beam, close the shutter, and observe the decay of isotopes such as $^{40}$Cl. We are currently investigating making measurements in neutron beamlines with dedicated detectors such as GEANIE (GERmanium Array for Neutron Induced Excitations) for high-precision measurements of production cross-sections that will be input to simulations in LBNE and will cross-check the measurements made in CAPTAIN to determine the efficiency.
3.3 Low-intensity neutron running

Low-intensity running allows us to correlate specific topologies with neutron kinetic energy via time of flight. Although they are named "low-energy neutron run" and "high-energy neutron run" both measurements will be performed at the same time, given the wide range of the continuous energy spectrum of the incoming neutrons.

3.3.1 Low-energy neutron run

The goal of a low intensity, low-energy neutron run is to measure an excitation spectrum in $^{40}\text{Ar}$ and to study the reconstruction capabilities of $^{40}\text{Ar}^*$ de-excitation events in a liquid argon TPC.

The detection of a galactic supernova neutrino burst in LBNE requires the capability to tag and identify the following charged-current (CC) and neutral-current (NC) interactions:

$$\nu_e + ^{40}\text{Ar} \rightarrow e^- + ^{40}\text{K}^*(CC)$$
$$\nu_x + ^{40}\text{Ar} \rightarrow \nu_x + ^{40}\text{Ar}^*(NC)$$

In order to gain insight into the neutral-current interaction we propose to place the CAPTAIN detector in the neutron beam at LANSCE and measure:

$$n + ^{40}\text{Ar} \rightarrow n + ^{40}\text{Ar}^*$$

This interaction will provide a test bed for identifying $^{40}\text{Ar}^*$ de-excitation events inside a liquid Argon TPC. The relationship between neutron-induced and neutrino-induced interactions on $^{40}\text{Ar}$ will be investigated by comparing the neutron beam data to Monte Carlo simulations of both types of events.

3.3.2 High-energy neutron run

The goal of a low-intensity, high-energy neutron run is to study neutron induced events in order to characterize their topology, multiplicity, and identity of the visible particles produced along with their kinematic properties. We plan to compare our results with existing models, improve them, and use them to simulate LBNE events.

The experiment will use neutrons above $\sim 400$ MeV, where pion production can occur and the relevant events can be clearly seen in a LAr TPC. The differential cross section of pion production on C, Al, Cu, and W has been measured. The observed $A^{2/3}$ dependence of the cross sections shows that these cross sections can be readily predicted in argon, even if final states are very uncertain. In LAr the $\pi^-$ will be absorbed on an argon nucleus leading to a variety of multi-nucleon final states.

Brooks et al. [14] did not observe anything beyond the pion, so measurements with CAPTAIN will provide further information on details of the interaction. CAPTAIN will also measure spallation events in the neutron beam and try to measure the effect of these events on LBNE electron neutrino appearance backgrounds.
3.4 Run Plans

We anticipate neutron running in early FY15. The 2015 run cycle begins in August of 2014 and continues through early calendar 2015. Proposals are due to the LANSCE PAC in mid-April of 2014, so we will prepare our proposals during FY14.
Chapter 4

Neutrinos

Beyond neutron running, there are several possibilities for neutrino running beginning in FY15 or FY16. Two promising possibilities are running in an on-axis position in the NuMI beamline and running with the neutrino flux created at the Spallation Neutron Source. We have carefully designed the cryostat and cryogenics systems such that they can be transported and operated in a variety of facilities with a minimum of safety or operational challenges. For example, the cryostat is ASME U-stamped.

4.1 Running at NuMI

LBNE will measure neutrino oscillation phenomena with a baseline of 1300 km using, primarily, the first oscillation maximum. At that baseline, the neutrino energies in the first maximum range from 1.5 to 5 GeV. Neutrino cross-sections are poorly understood on any nuclear target in this energy regime. For argon, the ArgoNEUT collaboration has produced the first and only inclusive cross-section measurement in the energy regime important for LBNE with 379 events \[15\] integrated over the neutrino spectrum produced by the NuMI low-energy tune. LBNE must use the full CC cross-section for the oscillation analysis and thus must have robust methods to determine the neutrino energy. A detailed study of interactions in the energy regime corresponding to the LBNE first maximum is crucial. The experiment simply will not work without it.

Figure 4.1 shows the state of the art for the exclusive channel: \(\nu_\mu p \rightarrow \mu^- p \pi^+ \pi^0\) on a free nucleon \[16\]. Clearly more data are crucial in an era of precision neutrino physics.

4.1.1 On-axis running in NuMI

The NuMI beamline was constructed for the MINOS experiment and will be running with the medium energy tune to support the Nova and Minerva experiments. The medium energy tune will provide an intense neutrino beam with a broad peak between approximately 1 and 10 GeV.
Figure 4.1: Existing measurements of the $\nu_\mu p \rightarrow \mu^- p \pi^+ \pi^0$ cross-section as a function of neutrino energy reproduced from Figure 24 of Formaggio and Zeller [16].

The NuMI running of the CAPTAIN detector in both a neutrino and antineutrino beam is an integral part of understanding the neutrino cross sections needed by LBNE, and liquid argon detectors in general, to interpret neutrino oscillation signals. Measurements of CAPTAIN in an on-axis position in the NuMI beam are complementary to low-energy neutrino measurements made using MicroBooNE; moreover, with a fiducial mass approximately 20 times larger than the ArgoNEUT detector, CAPTAIN will contain the hadronic system for a significant fraction of events. CAPTAIN will make high statistics measurements of neutrino interactions and cross-sections in a broad neutrino energy range, from pion production threshold to deep inelastic scattering.

The fine resolution of the detector will allow detailed studies of low energy protons that are often invisible in other neutrino detector technologies. In addition, liquid argon TPC’s give good separation between pions, protons and muons over a broad momentum range. With these characteristics, CAPTAIN will make detailed studies of charged-current (CC) and neutral-current (NC) inclusive and exclusive channels in the important and poorly understood neutrino energy range where baryon resonances dominate. The first oscillation maximum energy at LBNE (2-5 GeV) is similarly dominated by baryon resonances. The exclusive channels CAPTAIN will measure include single charged and neutral pion production and single photon production. Measurements near strange production threshold will also be made.

Since the NuMI running comes after the neutron running at LANSCE, we will employ the neutron-interaction identification techniques developed in CAPTAIN in the reconstruction of the energy of the hadronic system.

In addition to the physics program for this detector, running in a neutrino beam with similar characteristics to the proposed LBNE beam will provide validation of its technology, including exclusive particle reconstruction and identification, shower reconstruction, and
Figure 4.2: Each graphic shows the furthest distance any charged particles or electromagnetic showers travelled in the detector from the selection of contained events. The upper left figure shows quasielastic events. The upper right figure shows the same from events created via nucleon resonances. The lower figure shows the same from events created by deep inelastic scattering. The detector contains about 10 % of all interactions where “contained” is as defined in the text.
reconstruction of higher energy neutrino events with significant particle multiplicities.

Finally, in order to accommodate neutrino running, a simulation of neutrino interactions with argon with a neutrino energy spectrum of the on-axis, medium-energy NUMI tune was carried out. It was determined that the current geometry would contain 10% of all neutrino events where containment is defined to be “all but lepton and neutrons.” Depending on achieved POT, this will yield roughly 400,000 contained events per year. Distributions of the particle that travels the furthest from the vertex (with the exception of neutrons and leptons) is shown in Figure 4.2.

4.1.2 Off-axis running in NuMI

We may be able to deploy the CAPTAIN detector in front of the Nova near detector in an off-axis position. The off-axis NuMI beam provides a relatively narrow neutrino energy peak at about 2 GeV. Such running would provide a wealth of information at a specific neutrino energy close to the LBNE oscillation maximum. While interesting in its own right, the information would serve as a valuable lever arm for interpreting the broad-band on-axis data. Studies of this option are just beginning.

4.2 Running at the SNS

The measurement of the time evolution of the energy and flavor spectrum of neutrinos from supernovae can revolutionize our understanding of neutrino properties, supernova physics, and discover or tightly constrain non-standard neutrino interactions. LBNE has the capability to make precise measurements of supernova neutrinos. For example, collective neutrino oscillations imprint distinctive signatures on the time evolution of the neutrino spectrum that depend, in a dramatic fashion, on the neutrino mass hierarchy and mixing angle $\theta_{13}$. Current knowledge of the neutrino argon cross sections and interaction products at the relevant energies (<50 MeV) (there are no neutrino measurements in this energy range) limit the ability of detectors to extract information on neutrino properties from a supernova neutrino burst. Cascades of characteristic de-excitation gamma rays are expected to be associated with different interaction channels, which could enable flavor tagging and background reduction. Currently the ability of LArTPC detectors to observe these gamma rays (and accurately reconstruct their energy) is very uncertain. CAPTAIN will afford a nearly unique opportunity to measure key neutrino-nuclear cross sections in both the charged and neutral current channels that would allow us to make better use of the supernova neutrino burst signal.

The observation of 11 (mostly) anti-neutrino events from SN1987A confirmed the general model of supernovae explosions, demonstrating that the bulk of the gravitational binding energy, $8 \times 10^{52}$ ergs is released in the form of neutrinos. The LBNE detector with 34 kT of fiducial mass and an Argon target would detect more than 1000 events from a supernova at 10 kpc. There are four processes that can be used to detect of supernova neutrinos in a
The vast majority of these neutrinos would be detected via the first process above. Though small in number, the elastic scattering reaction preserves the neutrino direction, enabling localization of the direction of the supernova and the neutral current reaction allows for a calibration of the total energy released in neutrinos. While the elastic scattering cross section has been measured, the charged current reactions in argon have only theoretical predictions. In addition, while elastic scattering can also be measured in water Cherenkov detectors, the argon CC interaction is unique in that it has a large cross-section and has the potential to provide a better handle on the energy of the initial neutrino. The estimated theoretical uncertainty in the cross section calculations is stated to be 7%, however the authors note that a small change in the $Q$ value of the excited argon state could lead to a 10-15% change in the cross section.

It has recently been realized that the evolution of the neutrinos as they leave the protoneutron star surface is more complicated than previously believed. Collective oscillations of the late time (approximately 10-20 seconds after the neutronization burst) neutrinos leads to a spectral swap [17] shown in Figure 4.3. The figure shows the probability that a neutrino of species $x$ would survive without oscillating to another species as it propagates through the neutrinosphere. This survival probability is shown as a function of the neutrino energy (x-axis) and the emission angle from the protoneutron star (y-axis). The left panel is for the normal mass hierarchy and the right panel is for an inverted neutrino mass hierarchy. What can be seen is that in the normal hierarchy, all neutrinos with energy less than 10 MeV oscillate to a different species and all those above 10 MeV survive as the same species. For an inverted hierarchy it is just the opposite (the low-energy neutrinos survive without oscillation). Since the temperature (or energy spectrum) of the neutrinos is dependent upon the neutrino flavor, this spectral swap could be observed in a detector that is sensitive to electron neutrinos.

Extracting the physics from the detection of a Galactic supernova depends upon understanding of the neutrino argon cross sections, the ability to distinguish the neutrino charged current reaction given above from the anti-neutrino charged current reaction (which leads to an excited Cl nucleus), the ability to isolate the neutral current reaction, and the energy resolution of the detector.

To extract the neutrino physics from the detection of a supernova burst one needs to convert the measured electron neutrino spectrum to a source flux (as a function of energy) and to measure the complete (over all neutrino species) neutrino energy distribution. This will require accurate knowledge of the charged current cross section for converting Ar to K and the neutral current cross section for creating the excited $^{40}Ar$ state. In addition one
needs to clearly tag such events, which can be done by detecting (and measuring the energy of) the de-excitation gamma rays as the excited states of K, Ar or Cl decay.

We propose to run the CAPTAIN (Cryogenic Apparatus) LAr TPC at the SNS to:

- Measure the neutrino argon charged current cross sections in the energy region of interest.

- Investigate the capability of a liquid argon TPC to measure the de-excitation gamma rays from the excited nuclear states of Ar, Cl, and K).

- Measure the energy resolution of a liquid argon TPC at low energies in a realistic environment similar to operation of LBNE at the surface, to demonstrate that one can properly tag the events.

The Spallation Neutron Source in Oak Ridge, TN, provides a high-intensity source of neutrinos from stopped pions in a mercury target. The energy spectrum of the neutrinos from a stopped pion source is well known, has an endpoint near 50 MeV, and covers the energy range of supernova burst neutrinos. Figure 4.4 shows the SNS neutrino energy spectra and that of supernova burst neutrinos. The timing characteristics of this source will help reduce the neutron background, though shielding will most likely be required.

The interaction rates in argon are shown in Figure 4.5 as a function of distance and argon mass. A five-ton detector would measure thousands of events per year if sited sufficiently close to the target. Neutrino interaction cross-sections in argon and interaction product distributions, including de-excitation gammas, could be measured for the first time. Such an experiment would also be valuable for understanding the response of a LArTPC detector to neutrinos in this energy range.

Figure 4.3: Spectral swap of neutrino energy spectrum between normal hierarchy (left panel) and inverted hierarchy (right panel). The y-axis is the emission angle of the neutrino, which is not observable. The observed energy spectrum is the projection of these figures onto the x-axis. Figure from reference [17].
Figure 4.4: Neutrino energy spectra from supernova bursts neutrinos (solid lines) and the neutrino energy spectra from the stopped pion source at the SNS. Figure from reference [18]

Figure 4.5: Estimated event counts per year in argon as a function of detector mass and distance from the SNS target [18].

4.3 Stopped Pion Source at the BNB

The Booster Neutrino Beam (BNB) at FNAL was designed and built as a conventional neutrino beam with a decay region to produce pion-decay-in-flight neutrinos for the MiniBooNE experiment and will run to support the MicroBooNE experiment. Due to the short decay region, it also can serve as a source of neutrinos from stopped pions in the target, horn, and surrounding structures. It therefore could perform similar neutrino measurements as those outlined in the above section on the SNS. The maximum beam power the BNB is 32 kWatt, while the SNS is ~1 MWatt. While the SNS has a factor of 30 higher beam power, it is possible the CAPTAIN detector at the BNB could be built as close as 10m to the absorber.
At the SNS, it is likely the detector would be at least 20 to 30 meters away from the target. The BNB stopped pion flux at 10m from the absorber is estimated to be $2 \times 10^6 \nu/cm^2/s$, compared with $4.7 \times 10^6 \nu/cm^2/s$ [19] at 30m from the SNS target. The BNB may be a competitive choice for carrying out measurements of low-energy neutrinos. Further studies will be required to determine neutron background rates and if it becomes a limiting factor in how close the detector can be to the BNB absorber.

4.4 Other Neutrino Possibilities

There are other neutrino running possibilities. For example, space may be available in the SciBooNE hall in the Booster Neutrino Beamline at Fermilab. While preliminary studies do not demonstrate a significant benefit to MicroBooNE from running a 5-ton near detector, the situation could change if any anomalies arise in MicroBooNE’s first data.

Other spallation neutron sources exist around the world. If running at SNS or the BNB becomes problematic, there may be opportunities at other facilities.
Chapter 5

Conclusions

The CAPTAIN program will make significant contributions to the development of LBNE. It will make unique physics measurements that support most important LBNE missions including: the long-baseline neutrino oscillation program, the atmospheric neutrino program (and correlated WIMP search) and the supernova neutrino program. The detector will also serve as a test bed for various calibration and detection strategy schemes - especially regarding laser calibration and photon detection.

The scientific program of CAPTAIN will make unique measurements of neutron interactions in argon as well as detailed neutrino interaction measurements.
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