Letter of Intent for Fermilab Physics Advisory Committee

CAPTAIN-BNB: Measuring Supernova Neutrino Cross Sections in Liquid Argon Detector at the off-axis of Fermilab Booster Neutrino Beam

The CAPTAIN Collaboration

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EXECUTIVE SUMMARY

We propose an experiment to investigate low energy neutrino interactions using the CAPTAIN (Cryogenic Apparatus for Precision Tests of Argon Interactions with Neutrinos) liquid argon time projection chamber (LArTPC) exposed to a pion decay-at-rest low energy neutrino source at Fermilab. The goal is to provide the first measurements of neutrino cross-sections on an argon target with a focus of energy range in supernova interactions. The resultant work will also provide design parameters for the future of the deep-underground Long-Baseline Neutrino Facility (LBNF) in the U.S.

The recent P5 report restated the importance of low energy neutrino physics. The report explicitly specified that the future LBNF should have the demonstrated capability to search for supernova bursts as the large scale underground liquid argon detector has unique sensitivity to the electron-neutrino flavor. A facility that produces 10-MeV-scale neutrinos is required for such studies. We propose to use the low energy neutrinos from the pion decay-at-rest at the Booster Neutrino Beam (BNB) at Fermilab. The CAPTAIN detector is a 7,700 liters of LArTPC with a photo detection system deployed in a portable cryostat. This detector off-axis at the BNB expects several hundreds of neutrino events per year, which is sufficient to carry out decisive measurements of neutrino cross-sections.

The proposed research program will enable low energy neutrino cross section measurements on argon target. The proposed work includes the essential studies to prepare a shielding configuration for the experiment, deploy the CAPTAIN detector at the BNB site, detector operation and data analysis.

The SciBath neutral particle detector will be used to measure the neutron background at the BNB site. Then the concrete shielding structures will be installed for the CAPTAIN experiment using the available concrete shielding blocks from the Fermilab storage area. The CAPTAIN detector will subsequently be moved to Fermilab after completing its detector test at Los Alamos National Laboratory. The DAQ components will stay in the target building for easy access to the system and for weather control while the CAPTAIN cryostat will be placed in the concrete shielding structure. This particular setup allows the experiment to circumvent the substantial time and cost of civil engineering.

The detector operation would last about one year (or 4×10^{20}POT). The dataset will yield ample statistics of ν_e+Ar$\rightarrow$ e^-+K* events to claim the first ever measurement of charged current low energy neutrino cross-section on argon target. Further study of the characteristics of well-classified low energy neutrino interactions in the CAPTAIN detector will provide essential input to the future deep-underground LBNF program.

In summary, we are proposing a program to measure the neutrino cross-section on an argon target, which is relevant to the supernova neutrino energy range. The results of this work will not only deliver the first ever measurement of low energy neutrino cross-section on argon, but will also offer decisive detector design parameters for the LBNF. This task is practicable in a cost-effective way at Fermilab due to its existing resources and infrastructure.

A. INTRODUCTION

One of the most spectacular phenomenon in the night sky is the explosion of a massive star; the supernova. Supernovae enrich the interstellar medium with heavy mass elements, and the shock waves from their explosion can trigger the formation of new stars. Therefore, supernovae are where we all came from.

A core-collapse supernova produces tremendous amount of neutrinos of all flavors. The energy of these neutrinos are in the range of few-tens of MeV. Measuring the time evolution of the neutrino energy and flavor spectrum from supernovae can revolutionize our understanding of supernova physics and neutrino properties. The time structure of neutrino fluxes and neutrino flavors are directly related to the explosion mechanism of core-collapse supernova. At the early stage of the collapse, which occurs in the scale of a tenth-of-milliseconds, the breakout burst is dominated by ν_e from electron capture ($p + e^- \rightarrow n + \nu_e$). The burst is followed by an accretion phase that is tens to hundreds of milliseconds long and the subsequent cooling phase lasts for a few tens of seconds. During the cooling phase the core emits most of the gravitational binding energy and $\nu\bar{\nu}$ pairs dominate neutrino production. The neutrino flavors have an expected energy hierarchy of $\langle E_{\nu_e}\rangle < \langle E_{\bar{\nu}_e}\rangle < \langle E_{\nu_x}\rangle$, where ν_x represents $\nu_\mu, \nu_\tau, \bar{\nu}_\mu$, or $\bar{\nu}_\tau$. The ν_e have more interactions than the $\bar{\nu}_e$, because of the excess of neutrons in the core. On the other hand, the $\bar{\nu}_e$ have more interactions than the ν_x, which are restricted to neutral currents (NCs). The weaker the interactions the deeper the decoupling of the neutrinos from the star and, therefore, the hotter the temperature of the neutrinos at the surface of the neutrinosphere [1–6].

There may be significant variations in the expected flux from supernova to supernova due to differences in the mass and composition of the progenitor, asymmetries, rotational effects, or magnetic field effects. The nature of the supernova neutrino spectra and their time evolution depend on the mass and oscillation parameters of the neutrinos. The measurements are also sensitive to the neutrino mass hierarchy [7–14]. In some scenario [15], for a normal mass hierarchy, all neutrinos with energy less than 10 MeV oscillate to a different species and all above 10 MeV survive as the same species. For an inverted mass hierarchy, the opposite occurs. Since the temperature of the neutrinos is dependent upon the neutrino flavor, this spectral swap could be observed in a detector that is sensitive to electron neutrinos such as the liquid argon time projection chamber (LArTPC). A suggested mechanism for these spectral swaps are non-linear neutrino self-interactions which would become relevant at the very large neutrino densities accessible only to core-collapes supernovae. Furthermore the flux may carry signatures of oscillations involving sterile neutrino states [16]. The physics case of supernova neutrinos extend to other particle physics such as axions [17] or extra dimensions [18].

The only supernova neutrinos that have been observed in history was from SN1987A, a type-IIa core-collapse supernova in the Large Magellanic Cloud located 50 kpc away from Earth. Over a 13-seconds interval, a total of 26 neutrino interactions were simultaneously observed by two water Cherenkov detectors (Kamiokande-II [19] and IMB [20]) and a scintillator detector (Baksan [21]). All these observed neutrinos are almost certainly $\bar{\nu}_e$ flavors. Although the SN1987A was only a single occurrance, these experimental observations gave impact to a wide area of fields ranging from astrophysics, nuclear physics and particle physics for over 28 years and still continues. The last directly observed supernova in the Milky Way was in 1604 (SN1604). The rate of occurrence of core-collapse supernova in our galaxy is estimated to be about a few per century. According to the distributions of potential progenitors of supernova in the Milky Way, the most likely distance to the next supernova is approximately $\sim$10 kpc away. Since 1987, the detection capabilities of the supernova neutrinos have substantially improved due to currently operating large scale neutrino detectors worldwide, such as Super-Kamiokande, KamLAND, LVD, Borexino and HALO. However, most of these existing detectors are dominantly sensitive to the anti-electron-neutrino flavor via inverse beta decay interactions. The liquid argon target, on the other hand, has unique and exquisite sensitivity to the electron-neutrino flavor via charged current reaction (CC).

The planned Long-Baseline Neutrino Experiment detector [22] with 34 kton of liquid argon fiducial mass will be able to detect more than 2,000 neutrino events from a supernova at 10 kpc. There are four processes that can be used to detect supernova neutrinos in a liquid argon detector:

$$
\begin{aligned}
\nu_e\mathrm{ArCC}: &\quad \nu_e + {}^{40}Ar \;\rightarrow\; e^- + {}^{40}K^* \\
\bar{\nu}_e\mathrm{ArCC}: &\quad \bar{\nu}_e + {}^{40}Ar \;\rightarrow\; e^+ + {}^{40}Cl^* \\
\mathrm{ES}: &\quad \nu_x + e^- \;\rightarrow\; \nu_x + e^- \\
\nu_x\mathrm{ArNC}: &\quad \nu_x + {}^{40}Ar \;\rightarrow\; {}^{40}Ar^* + \gamma
\end{aligned}
$$

The vast majority of these neutrinos would be detected via the ν_eArCC process. The elastic scattering reaction (ES) preserves the neutrino direction, enabling localization of the direction of the supernova and the neutral current reaction (NC) allows for a calibration of the total energy released in neutrinos. Whereas the elastic scattering cross section has been measured, the charged current reactions in argon have only theoretical predictions with 15% uncertainty [23–26].

Figure 1 shows an example of a flux prediction of supernova neutrinos (left) and event rates in

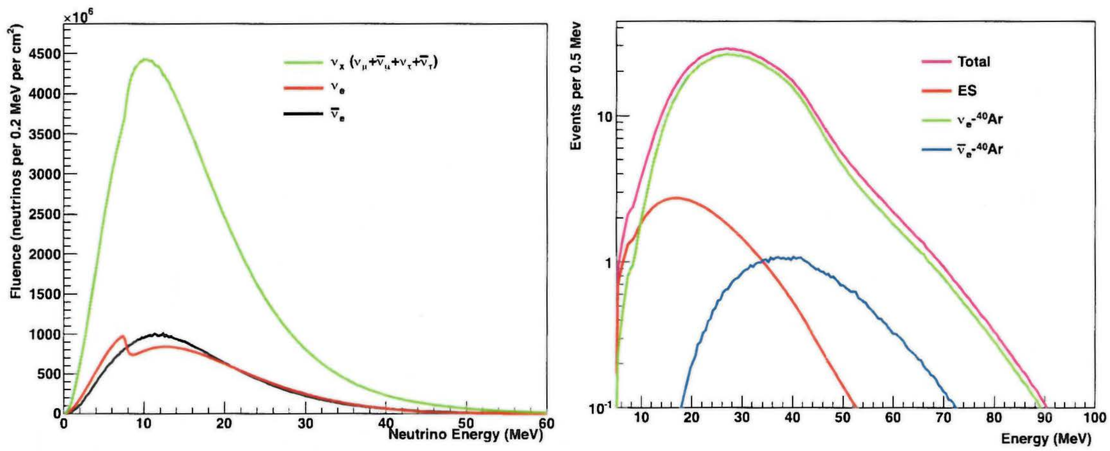

Figure 1: Left: Example of expected supernova neutrino spectra (integrated over 10 s) for the different flavor components; based on the Gava-Kneller-Volpe-McLaughlin model [5, 27]. Right: The expected supernova neutrino event rates in 17 kton of argon detector [27].

a 17 kton argon target detector (right) [5,27]. It is obvious that the supernova neutrino interactions in liquid argon detector are dominated by ν_eArCC events. As aforementioned, the outstanding sensitivity to the electron-neutrino flavor is the distinctive value of the LArTPC as a supernova neutrino detector compared to other types of detectors. In order to extract neutrino physics from the detection of a supernova burst, it is essential to convert the measured electron neutrino spectrum to a source flux and to compute 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 order to understand the event topology of these events and to measure the cross sections, these require (1) an intensive low energy neutrino source and (2) a LArTPC detector capable to measure the low energy neutrino interactions.

B. PROPOSAL

We propose a research program to study low energy neutrino interactions using the CAPTAIN (Cryogenic Apparatus for Precision Tests of Argon Interactions with Neutrinos) detector [28] exposed to a pion decay-at-rest (πDAR) neutrino source at the Fermilab's Booster Neutrino Beam (BNB) [29]. The scientific goals of this CAPTAIN-BNB program are:

- Measure the ν_eArCC cross section in the supernova neutrino energy ranges for the first time.
- Investigate the capability of a LArTPC to measure ν_xArNC.
- Understand the detector response of a LArTPC at low energy neutrino interactions.

This program is aligned with the recent P5 report [30] which emphasized the importance of low energy neutrino physics. The report also explicitly stated that the future Long-Baseline Neutrino Facility (LBNF) should have the demonstrated capability to search for supernova bursts.

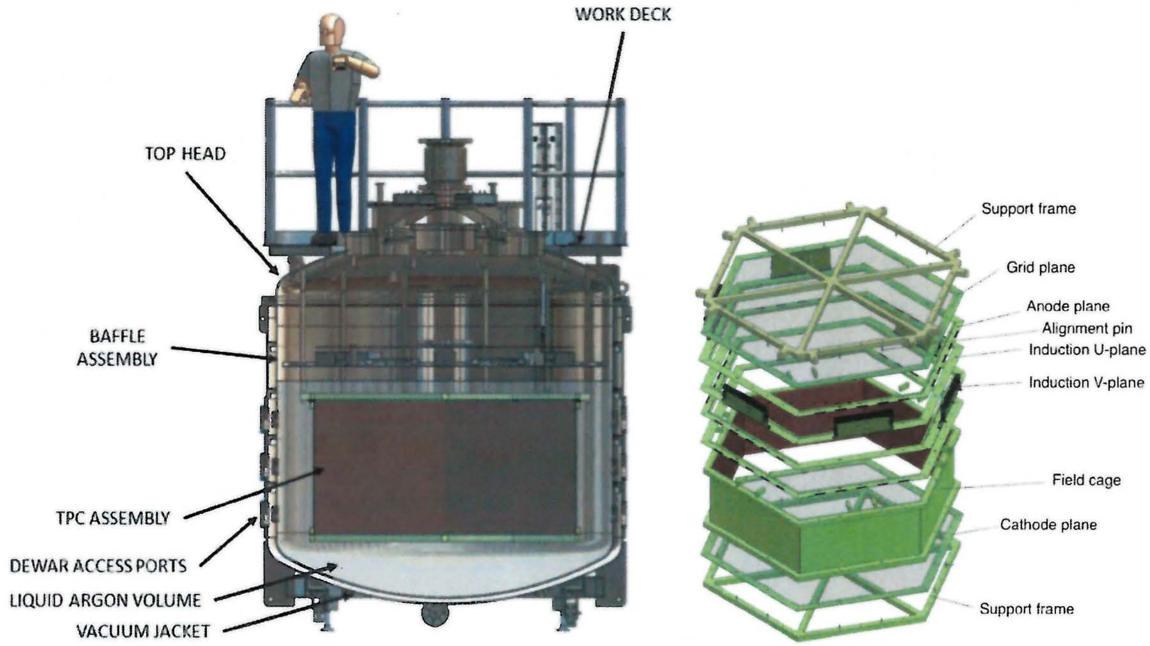

Figure 2: Schematic drawing of the CAPTAIN detector and a component view of TPC [28].

The proposed work includes essential studies for neutron background shielding, deploying the CAPTAIN detector at the BNB, operation of the detector, carrying out data analysis and publishing the results. We emphasize that this task is practicable in a cost-effective and timely manner at Fermilab due to Fermilab's existing infrastructure, technical and engineering human resources who developed LArTPC detectors, and consistent support from the lab on neutrino physics.

B1. The CAPTAIN detector

The CAPTAIN detector is a 5 ton fiducial mass LArTPC which is under construction at Los Alamos National Laboratory (LANL). The initial detector commissioning and test at LANL is to be completed in early 2016. The portable design of the detector system places the CAPTAIN program in a unique position to address many aspects of scientific and technical issues pertaining to a LArTPC. The detector is particularly suitable to study the neutrino interactions in the energy range of supernova neutrinos, in which the interactions would be fully contained in the detector fiducial volume. Figure 2 shows the schematic drawing of the detector and component view of TPC. The chamber can hold a total of 7,700 liters of liquid argon instrumented with a 2,000 channel TPC and a photon detection system. The outer cryostat is 107.5 inches in diameter and 115 inches tall. 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.

The liquid argon purification system design of CAPTAIN is based on that from MicroBooNE [31] and the Liquid Argon Purity Demonstration [32] at Fermilab. The CAPTAIN's dual filter system consists of a bed of molecular sieve (208604-5KG Type 4A) to remove water molecules and another bed of activated copper material (CU-0226 S 14 X 28) to remove oxygen molecules. To achieve a sufficiently long drift-distance for electrons, the O_2 contamination is required to be smaller than 240 ppt. Quenching and absorption of scintillation light have been demonstrated [33, 34] to be negligible when the N_2 contamination is smaller than 2 ppm. Commercial analytic instruments will be used to characterize the oxygen and water contaminant levels in the argon.

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; a grid, U, V, and collection (anode) plane. All wire planes have 75 μm 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 ± 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 consists of a drift cage module and a 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 a 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/μs.

The electronic readout components for the TPC are identical to those of the MicroBooNE experiment [31]. The front-end mother board is designed with twelve custom CMOS Application Specific Integrated Circuits (ASIC) which reads out 16 channels from the TPC. The output signals from the mother board are transmitted to the intermediate amplifier board which is driving the differential signals to the 64 channel receiver ADC board. The digital signal is then processed in an FPGA on the Front End Module board. These signals are transmitted to the data acquisition computer.

Liquid argon scintillates at a wavelength of 128 nm. The photon detection system is composed of a wavelength shifter (TetraPhenyl Butadiene) covering a large area of the detector and a number of photodetectors to collect the visible light. The base design consists with twenty four Hamamatsu R8520-500 photomultiplier tubes (PMT) for light detection in cryogenic temperature, twelve on top and twelve on bottom. It has a 25% quantum efficiency at 340 nm, expecting 3.3 photoelectrons/MeV for a Minimum Ionizing Particle. The PMT signals will be digitized at 250 MHz using three 8-channel CAEN V1720 boards. The digitizers are readout through fiber optic cables

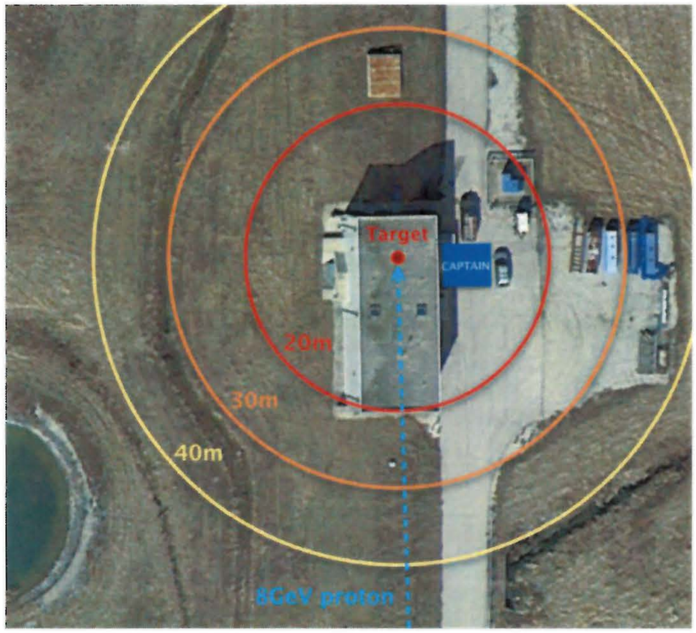

Figure 3: The configuration around the BNB target building area. The BNB target building dimension is about 10 m wide and 26 m long. The red dot in the figure indicates the location of the target. The blue box indicates the proposed CAPTAIN experiment site.

by a data acquisition system [35].

There are two key design issues of the future LArTPC supernova neutrino detector; (1) the photo-coverage and (2) the wire-spacing. The detector parameters of the CAPTAIN would be refined via detailed detector simulation after series of calibrations. However decisive design parameters can only be learned by directly measuring the low energy neutrino interactions. For example, the photo-coverage of the PMTs would substantially improve the event reconstruction and energy resolution of the low energy neutrino interactions. It would be worthwhile to investigate the optimal spacing of the wires for the efficient detection of the low energy neutrino interactions. The proposed work will carefully study these detector design issues.

B2. Low Energy Neutrino Source at Fermilab

In order to understand the low energy neutrino interactions in the LArTPC, it is essential to have a well defined low energy neutrino source with a suppressed background configuration. The BNB at Fermilab 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. A recently published work [29] has shown that the BNB is a powerful source of πDAR neutrinos at far-off-axis locations. Figure 3 shows the BNB target building area and the proposed CAPTAIN experiment site.

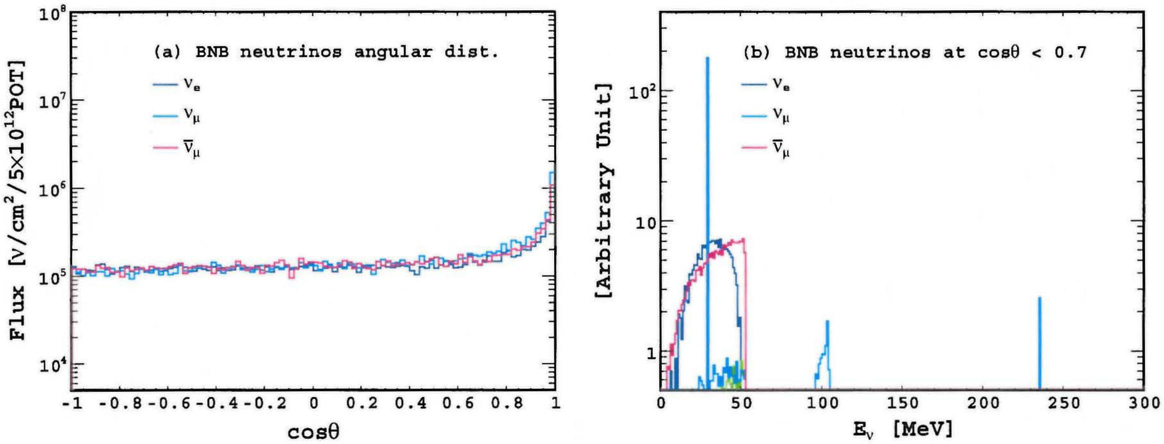

Figure 4: Estimated neutrino flux from modified BNB MC in ν-mode, 173 kA horn current and 8 GeV booster beam configuration. The neutrino flux is normalized per 5×10^{12} protons on target. (a) The angular dependence of the neutrino fluxes for different flavors. The flux becomes uniform below $\cos\theta < 0.7$. See text for the definition of θ. (b) Energy spectrum of neutrinos below $\cos\theta < 0.7$ (far-off-axis) for different flavors [29].

The proposed site, close to the BNB target, allows optimal placement of the detectors with minimal sitting issues. The CAPTAIN experiment would be completely unobstructive to any operation of the BNB. It would require no changes to the beamline and place no additional requirements on the running mode or times. The πDAR neutrinos from the BNB are a by-product of running the beamline for MicroBooNE and other planned short-baseline neutrino experiments. The BNB beam will continuously be available for the foreseeable future.

The Fermilab Booster is a 474-meter-circumference synchrotron operating at 15 Hz. Protons from the Fermilab LINAC are injected at 400 MeV and accelerated to 8 GeV kinetic energy. The structure of the beam is a series of 81 proton bunches each with a 2 ns width and 19 ns apart. The maximum average repetition rate for proton delivery to the BNB is 5 Hz and 5×10^{12} protons per pulse. The repetition limit (5 Hz) is set by the horn design and its power supply. The scheduled beam mode for the next several years will be 2.5 Hz (16 kW), half of the maximum beam power. The target is made of beryllium divided in seven cylindrical sections in a total of 71.1 cm in length and 0.51 cm in radius. In order to minimize upstream proton interactions, the vacuum of the beam pipe extends to about 152 cm upstream of the target. The horn is an aluminum alloy toroidal electromagnet with operating values of 174 kA and maximum field value of 1.5 Tesla. A concrete collimator is located downstream of the target and guides the beam into the decay region. The air-filled cylindrical decay region extends for 45 meters. The beam stop is made of steel and concrete. Details of the Fermilab BNB performance and neutrino fluxes at on-axis can be found in [36].

In order to properly model the target geometry of the stopping pion decay region, we adopted the Booster Beam MC which was developed by the MiniBooNE collaboration. The BNB MC sim-

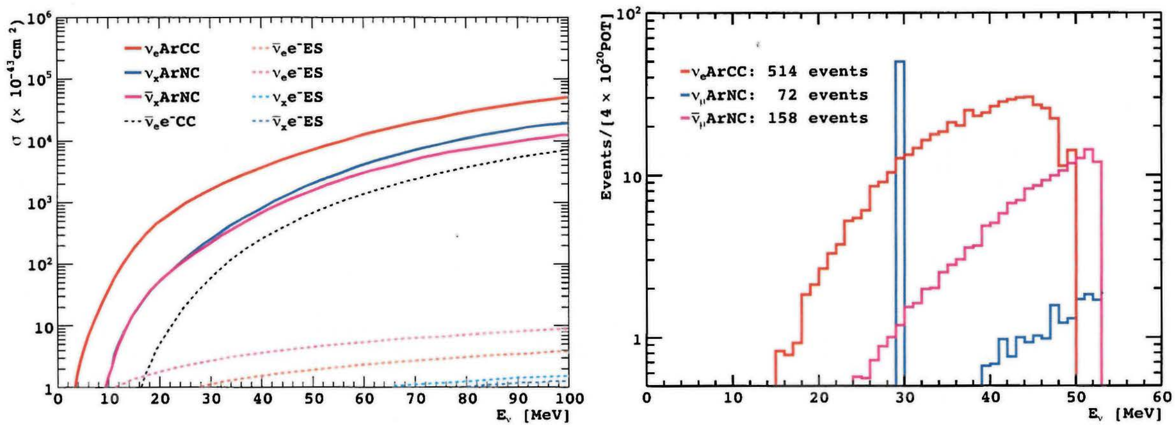

Figure 5: The left figure shows the neutrino cross sections relevant to the supernovae detection with an argon TPC detector [37]. The right figure shows the neutrino interaction rates in the CAPTAIN detector for each neutrino flavor as a function of incident neutrino energy at 10 m away from the BNB target. Note, the detector (LArTPC) response of these neutrino interactions is not well understood and is a part of the proposed study.

ulation was carried out in neutrino mode with 173 kA horn current and 8 GeV proton momentum. Figure 4(a) shows the angular distribution of the neutrino flux 20 m away from a reference point of the upstream end of the decay pipe where the angle is measured from on-axis. The flux of the neutrinos, at the 32 kW maximum Booster power (5×10^{12} protons on target per pulse), is estimated to be about $10^5 \nu/\mathrm{cm}^2$/pulse per flavor with 5 Hz frequency within a pulse width of 1.6 μs. Hence, the neutrino flux per unit time is about $5 \times 10^5 \nu/\mathrm{cm}^2/\mathrm{s}$. Figure 4(b) shows the energy spectrum of neutrinos at angles less than $\cos\theta < 0.7$ which is dominated by neutrinos from stopping pion decay. The pion decay at rest ($\pi^+ \rightarrow \mu^+ \nu_\mu$) produces a prompt and monochromatic ν_μ at 29.9 MeV. The μ^+ then decays on a 2.2 μs timescale to produce a $\bar{\nu}_\mu$ and a ν_e with energies between 0 and $m_\mu/2$. In Figure 4(b), the ν_μ, ν_e and $\bar{\nu}_\mu$ spectra follow the stopping π^+ decay kinematics. The small ν_μ bump at $\sim$100 MeV is due to the neutrinos from μ^- capture on nuclei. The peak at 235.3 MeV is from kaon decay at rest. These ν_μs above 50 MeV are potential background sources since the interaction of neutrinos may scatter off neutrons from nuclei nearby or inside the detector. Depending on the neutron background shielding configuration, the CAPTAIN detector can be placed as close as $\sim$10 m away from the target. The expected neutrino flux at that location is then about $1 \times 10^6 /\mathrm{cm}^2/\mathrm{s}$ per flavor at 16 kW of normal operation mode of BNB for the next several years. The uncertainty in neutrino production from stopped pions and muons is dominated by the uncertainty of the pion production in the BNB target and surrounding materials. The uncertainty of the neutrino flux is about 9% [29].

B3. Neutrino Interactions in CAPTAIN

Experimental measurement of the low energy neutrino cross sections on argon target is an essential input to develop accurate simulation tools and hence to understand the design parameters

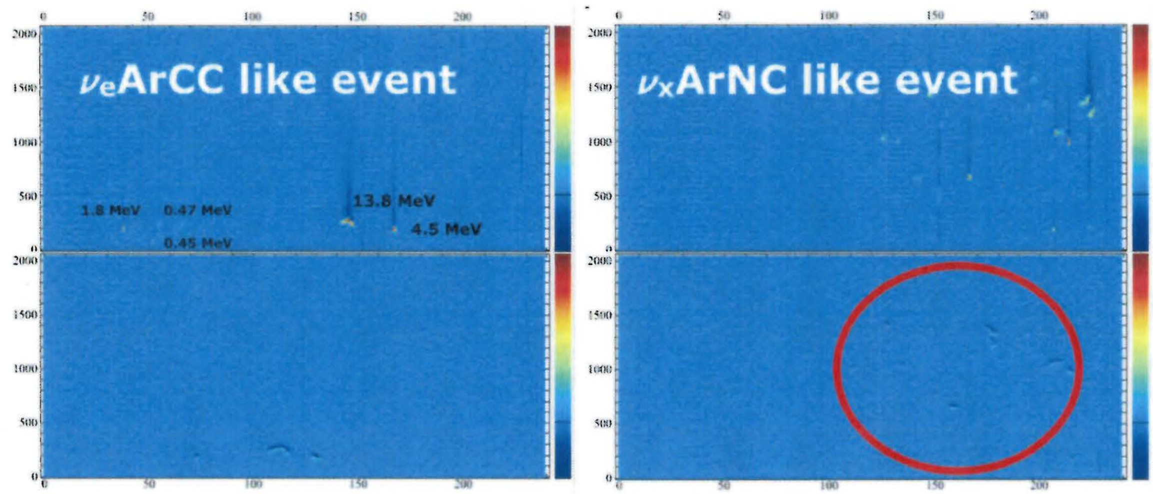

Figure 6: Events displays from ArgoNeuT NuMI operation [38,39]. The left figure shows an event topology that might look like a ν_eArCC event. The right figure shows an event topology that might look like a νArNC event.

for the future supernova neutrino detector on argon target.

Figure 5 (left) shows the neutrino cross sections relevant to the detection of supernovae and πDAR neutrinos. The right figure shows the expected neutrino interaction rates in 5 ton fiducial mass of CAPTAIN detector exposed by 4×10^{20} POT (16 kW and one-year operation) at 10 m away from the target. The ν_eArCC interaction rate is expected to be 514 events per year, $\bar{\nu}_\mu$ArNC interaction is 72 events per year and ν_μArNC interaction is 158 events per year. Note that the majority of supernova neutrino events in the LArTPC will be ν_eArCC interactions (see Figure 1). Therefore, the BNB πDAR source amply serves the purpose of the experiment.

The signature of ν_eArCC ($\nu_e + {}^{40}Ar \rightarrow e^- + {}^{40}K^*$) event in LArTPC would be one leading track of electron (squiggle; $\sim$10s of wires) and a number of small hits of electrons (spots; 1 to 3 wires). The spots are from cascade of de-excitation γs from Ar-K* transitions and continuous level density with statistical emission at higher excitations. Figure 6 shows event displays from the ArgoNeuT NuMI operation [38,39]. The left figure shows an event from the NuMI beam trigger. The interaction occurred just outside the TPC and then punched through the active detector region. The electron track deposited 13.8 MeV of energy and is relatively easy to identify. This electron track should be accompanied by Compton scattering electron spots of a few MeV. An event tagged by a combination of these features might be the one initiated by a ν_eArCC event. The goal of this measurement is to collect ample statistics of these events and to measure the cross section to within 10% accuracy.

The detector responses to $\bar{\nu}_\mu$ArNC and ν_μArNC interactions would be identical ($\nu + {}^{40}Ar \rightarrow {}^{40}Ar^* + \gamma$) in the LArTPC, where the signature is the de-excitation γs that deposit a few MeV in the detector. Figure 6 (right) shows an event that might look like the νArNC interaction (the events

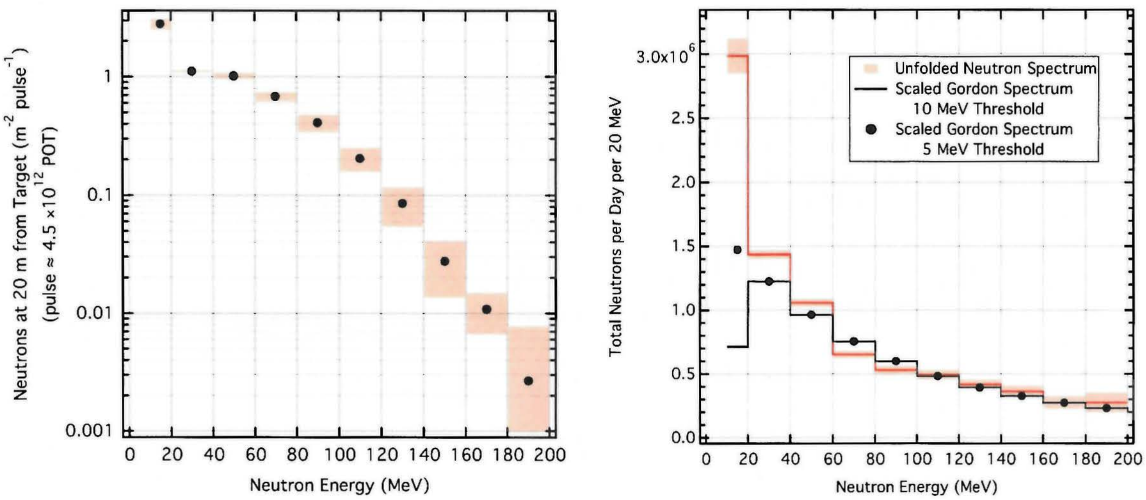

Figure 7: The measured beam-induced neutron energy spectrum (left) and cosmogenic neutron energy spectrum (right) by SciBath at 20 m up-stream of the BNB proton target [29].

in the red circle). Identifying these events is quite challenging since the characteristic of the event is just a several *spots* of Compton scattering electrons in the detector. The major background of these events is the inelastic scattering of argon by neutrons ($n + {}^{40}Ar \rightarrow {}^{40}Ar^{*} + \gamma$) which leaves very similar ${}^{40}Ar^{*}$ de-excitation gammas. However, there is a major difference between a neutrino interaction and a neutron interaction. A neutrino interaction may excite only one argon atom in the detector, while a neutron may scatter multiple times and excite many argon atoms. The CAPTAIN program at LANL is planning a neutron beam test of the detector. The study will be important to understand the background fraction of the neutron interactions (a single scatter neutron events) at a given neutron energy. In addition to the neutron calibration, the precise understanding of the neutron flux and energy spectrum at the BNB site is essential for the νArNC background study.

B4. Neutron Shielding

The existing radioactive shielding at the BNB target area (MI-12) is quite extensive and carefully thought out in order to satisfy the Fermilab radioactive safety regulations [40]. The target itself is located $\sim$6 m underground from the building surface. The shielding pile consists of iron blocks totaling 2.6 m in elevation (1,600 tons), an additional 2.5 m-thick concrete shielding (300 tons), and special custom sized steel (40 tons) above and below the horn module. About 10^{13} neutrons per beam pulse are expected to be initially produced at the target. These neutrons are produced in the forward beam direction with a maximum kinetic energy of $\sim$8 GeV with more than 90% of neutrons below 50 MeV. Before the scheduled beam shutdown in 2012, the CENNS collaboration measured the beam-correlated neutron flux and energy spectrum using the SciBath neutral particle detector [41, 42]. The measured neutron flux in the upstream of the BNB target building is 6.3 neutrons per m^2 per beam pulse above 10 MeV at 20 m from the target [29] which is

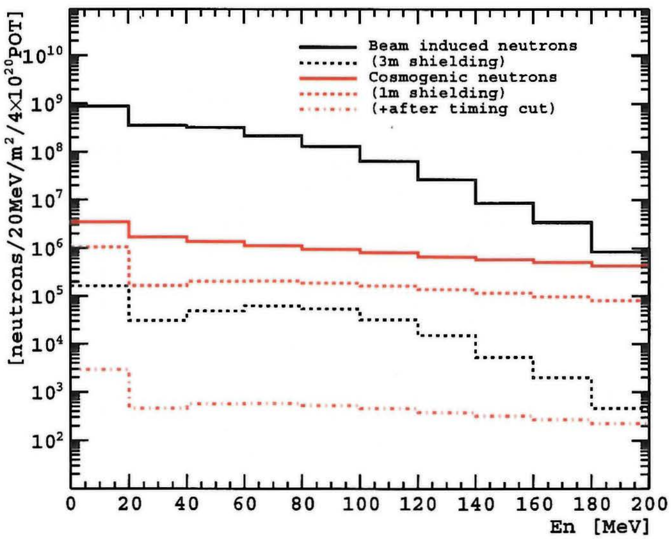

Figure 8: Neutron flux reduction with and without concrete shielding. The black solid histogram is the beam-induced neutrons and red solid histogram is the cosmogenic neutrons which are scaled from the measured values [29]. The black dotted histogram is the beam-induced neutron flux after passing 3 m of concrete shielding. The red dotted histogram is the cosmogenic neutron flux after passing 1 m of concrete shielding. The red dash-dotted histogram shows the cosmogenic neutron flux after considering event start-time cut.

shown in Figure 7 (left). The measured cosmogenic neutron flux is shown in the Figure 7 (right). These neutrons can become serious backgrounds for the CAPTAIN-BNB experiment.

The neutron event rate in the CAPTAIN detector without shielding would be about ~ 25 per beam pulse at 10 m from the target. This is an exceedingly high rate to carry out the experiment. Figure 8 shows the MC study of neutron fluxes without and with 3 m (1 m) of concrete shielding for the case of beam-induced (cosmogenic) neutrons. In this figure, the beam-induced neutron fluxes are scaled to 4×10^{20}POT and 10 m distance from the target. For the cosmogenic neutrons, detector livetime (1.8 ms per trigger) corrections are made.

We carried out a preliminary detector simulation (Geant4) assuming 3 m of concrete shielding and equivalent neutron statistics for 1-year detector operation. The interaction rate of beam-induced neutrons in the 5 ton fiducial CAPTAIN detector is about 5×10^{-3} events per beam pulse. The event rate in the energy region of interest (2 MeV to 50 MeV of total energy deposit) is about 4×10^{-4} events per pulse. For low energy neutron events below 10 MeV, the secondary particles are produced with multiple tracks of electrons, positrons, gammas and recoiled argon nucleus. For the higher energy neutrons, the events are accompanied by additional particles such as protons, alphas, deuterons, and tritons. By eliminating events that contain too many secondary particles (more than 20 particles) and long tracks (longer than 10 cm), no neutron induced events are left in the energy region of interest. Therefore, understanding the details of the event topology of neutron events in the detector is extremely important to distinguish the neutron interactions from the ν_eArCC. It is known that the neutron interactions above 20 MeV on argon target are not quite accurately modeled in the Geant4 package. Therefor, it is vital to carry out actual measurements of neutron interactions on LArTPC for various neutron energies. A series of planned neutron calibration campaigns of the CAPTAIN detector at LANL will provide valuable inputs to this study. The preliminary simulation results should then be further refined by full detector simulations that include detector parameters of the TPC and the PMT systems.

The timing of the individual events can be known to within ~10 ns using fast scintillation signals. The neutrino signals are expected within 1.6 μs of the beam time window. Therefore, the dangerous slow neutrons can be further reduced by using the event start-time information. The cosmogenic neutron interactions after 1 m concrete shielding are expected to be 0.04 events per beam trigger within 1.8 ms of detector time window. These cosmogenic neutron backgrounds are evenly distributed over the 1.8 ms. Therefore, a three orders of magnitude of these events will be eliminated by using the event start-time information. For example, the dash-dotted histogram in Figure 8 shows the cosmogenic neutron backgrounds in a 5 μs of event start-time-window which is a conservative assumption.

In the first project year, we plan to deploy a suite of neutron detectors to measure the neutron flux at the CAPTAIN-BNB site. They consist of the SciBath detector (see Figure A.1) and a liquid scintillator neutron detector array (EJ-301, see Figure A.2). The SciBath neutral particle tracking detector is a 70-kg, mineral oil based liquid-scintillator built at Indiana University. The cubic volume of scintillator is read out on each axis by a 16×16 array of wavelength shifting fibers, oriented along each detector axis with a spacing of 2.5 cm (768 total fibers). These fibers are individually read out with multi-anode PMTs. This readout gives the SciBath unprecedented uniformity for particle track reconstruction. The detector is small enough to be housed in a climate-controlled, commercially available, mobile trailer (8'H×8'W×12'L). A 5-kg array of EJ-301 liquid scintillator detectors will also be deployed to complement the SciBath detector. This detector is capable of discriminating gammas and neutrons through pulse-shape-discrimination of PMT waveforms and is sensitive to 0.5-20 MeV neutrons. Therefore, a large range of neutron energies can be measured with the tandem use of the SciBath detector and the EJ-301 liquid scintillator detectors. Both detectors are well characterized and the performance of these detectors have been demonstrated in a recent publication [29].

A preliminary design of the shielding block structure is a 3 m thick × 3 m wide × 3 m high concrete wall facing toward the target building, and 3 m thick × 6 m long × 3 m wide concrete side walls facing up-stream and down-stream of the beam directions. We may consider a concrete shielding ceiling about 1 m thick on top of the concrete walls depending on the detector performance on the cosmogenic background rejection. These concrete structures would provide a shielded experimental hall of 3 m×3 m×3 m. We will deploy the SciBath detector and EJ-301 detector array in the hall to carry out the beam-induced and cosmogenic neutron flux measurements. According to an MC study, it will take approximately three months to measure an order of 10^4 beam induced neutron events which will be enough to characterize the energy spectrum of the neutrons.

One of the most expensive components of the experiment are the concrete shielding blocks. Fortunately, there are many underutilized concrete shielding blocks across the Fermilab campus (a few examples are shown in Figure A.3), and the custodians of these concrete blocks have assured that they will be available if this project gets approved (D. Augustine and C. Rogers, Fermilab Accelerator Division). We will use these concrete blocks to assemble a shielding structure. Fermilab also has a heavy-duty mobile crane (Figure A.4) to configure the concrete blocks which will be available for this work (J. Voirin, Fermilab Particle Physics Division). We consulted Fermilab ESH&Q in order to assure the stability and safety of the concrete structures.

For the neutron shielding study, we plan to use MCNPX as our primary simulation tool and Geant4 as a complementary tool. The measured shielding parameters such as the flux reduction factor and the spectral change of neutron energy will be inputs into these simulation packages. The ultimate goal of the neutron shielding study is to perfect the construction of the neutron shielding for the CAPTAIN-BNB experiment. The results of the neutron shielding study will be submitted to a journal for publication as soon as the analysis is completed. It will be a valuable input to the other proposed low energy neutrino experiments at the BNB off-axis locations [29].

B5. CAPTAIN-BNB

The CAPTAIN detector will be moved to Fermilab after completing its detector test at LANL in the first project year. The design of the CAPTAIN detector equipment assured a small and modularized system profile, hence it can be transported by a standard flatbed truck. The detector will be initially deployed at the BNB target building service area (6 m long $\times$10 m wide $\times$ 9 m high) for the detector reassembly, cryogenics test, alarm system test, beam-induced electric noise test, data acquisition (DAQ) setup, local network setup, and beam trigger test. The Oxygen Deficiency Hazard and other basic safety issues will be addressed by the Fermilab engineers. The lifting power of the crane in the building is 30 ton (at 6 m high), hence, there is adequate lifting capacity to carry out the CAPTAIN detector reassembly work. The extra electric power in the building is sufficient to handle the required CAPTAIN operation (30 kW, 480 3-phase power supply for cryogenics and about 2 kW for electronics).

After the completion of initial detector tests, the detector will be carefully relocated to the CAPTAIN-BNB hall, about 10 m of moving distance. The DAQ, slow control system, monitoring computers and other equipments that require climate control will stay in the target building. These systems will be connected through the wall of the target building. This particular experiment setup saves huge cost in civil engineering as there is no need for a separate experiment building and other additional infrastructure.

The BNB beam delivery is scheduled for early 2015 with 16 kW of beam power for the Micro-

BooNE experiment. We expect the full operation of the CAPTAIN-BNB experiment to take about two years or more. According to the recent Fermilab short-baseline neutrino project plan, in addition to the MicroBooNE experiment, two more on-axis short baseline programs (LAr1-ND and ICARUSat-Fermilab) are planned at the BNB. Therefore, if possible, it would be extremely advantageous to collect a few thousand ν_eArCC events beyond the proposed CAPTAIN-BNB operation schedule. This will allow an accurate measurement of the energy spectrum for this important supernova neutrino detection channel.

There will be four data acquisition modes of the CAPTAIN-BNB: (1) Normal in-beam trigger mode for neutrino cross section measurement, (2) off-beam random trigger mode for cosmogenic background measurement, (3) Nd-YAG laser mode for the particle track calibration in TPC [43,44], and (4) LED calibration mode for single photoelectrons and multiple photon response tests. We will rely on the Accelerator Division at Fermilab for the beam condition monitoring and proton flux monitoring. The slow control parameters of the detector will be monitored by the local and remote shifters of the CAPTAIN collaboration. The expected raw data size per trigger is about 7 MB (TPC + PMT data). Since the CAPTAIN event traces are mostly baselines for both TPC and PMT traces, it is reasonable to assume 1/10 reduction factor by the zero-suppression of the data, hence ~0.7 MB per trigger. A local data server at BNB (32-core, 80 TB RAID disk array server) would be enough to store the entire data set over a year. We also plan to make a backup of the data on two 80 TB data servers (a total 160 TB) located at the Feynman Computing Center (FCC) at Fermilab. The BNB building is equipped with local network service which has enough extra capacity for the required 2 MB/s of data transfer to a main storage area at FCC. The data transfer rate has already been tested in 2012.

A group in the CAPTAIN collaboration is developing a generic CAPTAIN offline data analysis software package. As described in section $B2$, the signature of a ν_eArCC event in the LArTPC is a 10s of MeV electron *squiggle* and several Compton electron *spot*s of a few MeV. Therefore, understanding the noise performance of each wire and low energy electron response of the detector are important factors to identify neutrino interactions. They are also important to determine the detection efficiencies of neutrinos. These efforts also include careful studies of the timing of individual events and use of fast scintillation signal in order to remove the slow neutron backgrounds. The ultimate goal of this study is to identify the signature of ν_eArCC ($\nu_e + {}^{40}Ar \rightarrow e^- + {}^{40}K^*$) events and measure the cross section of this interaction.

We plan to study the νArNC ($\nu + {}^{40}Ar \rightarrow {}^{40}Ar^* + \gamma$) interactions. This particular analysis requires in-depth understanding of the neutron backgrounds ($n + {}^{40}Ar \rightarrow {}^{40}Ar^* + \gamma$) and their interactions in the LArTPC detector. It is unlikely that the pulse shape of the scintillation light from the argon nuclear recoils provide any differences between neutrino scattering and neutron scattering, although it may help to discriminate other backgrounds. Therefore, it is important to understand additional features of low energy neutron interactions in the LArTPC. The detector fiducial volume may need to be further refined for this study, because the low energy neutron scattering events may stay on the outer surface of the detector and will scatter multiple times while the neutrino interactions will be uniformly distributed inside the detector volume and will scatter only once. The event start-time information would also help to eliminate the low energy neutron events. With all these collective features, the LArTPC detector may be able to discriminate the νArNC from the neutron backgrounds. This is of high relevance in detecting supernova neutrinos at the future LBNF detector where the expected νArNC rate is of the order of a hundred in 10s of seconds, which will be very distinctive from the background neutrons with their steady interaction rate. Thus it is valuable to understand the event topology of the νArNC interactions in the LArTPC. The CAPTAIN-BNB provides a natural environment to challenge this important subject.

C. PROJECT TIMELINE

In this section, the details of the project timeline are outlined. Some technical issues are related to scheduling are discussed and contingencies are allocated for those cases.

Year 1 The focus of the first year is to construct the CAPTAIN-BNB shielding structure at BNB. Neutron flux measurements will be carried out using the SciBath and EJ-301 detectors without and with concrete shielding. The data analysis software for SciBath and EJ-301s were ready in 2013; therefore if there are any unexpected excess of fast neutrons through the concrete shielding, it can be found out almost immediately. We plan to address these shielding issues in order to achieve the goal of reducing the flux of the beam-induced neutrons by more than three orders of magnitude. Three months of SciBath operation will be sufficient to collect more than 10^4 neutron events in the CAPTAIN-BNB site. We scheduled for a six months operation of the SciBath detector to give enough contingency of data collection time and to address any shielding issues. The CAPTAIN detector will be moved from LANL to Fermilab as soon as the neutron calibration of the detector completed.

Year 2: The CAPTAIN detector will be carefully moved to the experiment site. Thanks to the modularized CAPTAIN detector system, the reassembly and initial detector test would take about a few months. We expect the detector commissioning and the full detector operation with stable condition within a few months. We expect about 500 ν_eArCC interactions in the 5 ton fiducial volume of the CAPTAIN detector in one year detector operation (or total 4×10^{20} POT). Even if we assume detection efficiency of 50%, the observed number of signal events would be enough to claim 10% measurement of the ν_eArCC cross section (note that the uncertainty of neutrino flux at BNB is about 9%).

Year 3: The goal of the project year-3 is to complete the CAPTAIN-BNB operation and finalize the data analysis of the ν_eArCC cross section measurement. The results will also include the first study of the LBNF detector design parameters. The CAPTAIN-BNB experiment will then be decommissioned by the end of the third project year. The data analysis will continue to obtain the experiment's fullest sensitivity. The final results including the studies of ν_eArCC and νArNC interactions, background study of the supernova neutrino detection and LBNF design issues will be summarized and be published.

Contingency of the schedule: The operational schedule of the CAPTAIN-BNB experiment is contingent upon the scientific and technical beneficiaries and risks. See CAPTAIN-MINERνA LOI for options of the operational schedules.

E. SUMMARY

We propose a research program to measure the neutrino cross section on argon target, which is relevant to the supernova neutrino energy range. The method is to expose the CAPTAIN LArTPC to the pion decay-at-rest low energy neutrino source at the Fermilab BNB. The results from this work will deliver the first ever measurement of low energy neutrino cross section on argon target, a crucial measurement to understand the supernova capability of a LArTPC. The work will also offer decisive design parameters for the future LBNF/E detector. This task is practicable in a cost-effective way at Fermilab due to its existing resources and infrastructure.

APPENDIX

In the following, we show the equipments that will be used for the neutron shielding study, such as SciBath detector (see Figure A.1), EJ-301 neutron detector (see Figure A.2), concrete shielding blocks (see Figure A.3), and heavy duty crane (see Figure A.4).

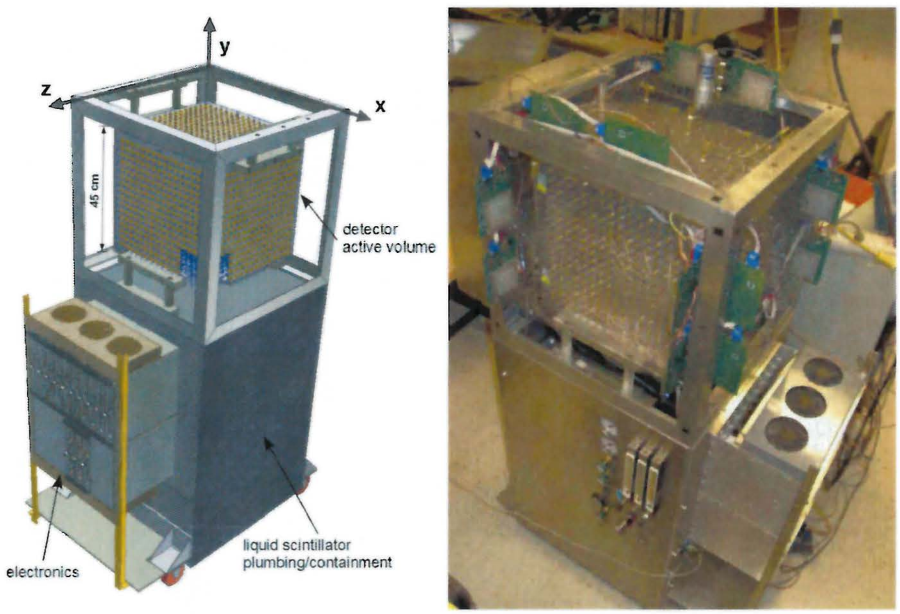

Figure A.1: A schematic drawing (left) and a photograph (right) of the SciBath detector with its $(45\,\mathrm{cm})^3$ active volume indicated along with the other major components. We demonstrated the performance of the SciBath detector for neutron spectrum measurement at BNB in reference [29].

Figure A.2: EJ-301 neutron detector array (left) and its DAQ (right). We demonstrated the performance of the EJ-301 detector for neutron flux measurement at BNB in reference [29].

Figure A.3: Typical concrete shielding-blocks at Fermilab. There are many other types and size of concrete shielding blocks, and more than enough shielding blocks are available for our project.

Figure A.4: Heavy duty (70 ton lifting power) crane at Fermilab. The crane will be available for the proposed concrete shielding work.

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