CAPTAIN-MINERvA: Neutrino-Argon Scattering in a Medium-Energy Neutrino Beam

The MINERvA and CAPTAIN Collaborations

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1 Executive Summary

Neutrino-nucleus interaction measurements are vitally important to neutrino oscillation experiments which must determine the incoming neutrino flavor and energy by measuring only the final state particles, using targets of complex nuclei. The MINERvA experiment is currently studying neutrino interactions on a variety of nuclear targets from helium to lead to provide much-needed constraints on models of nuclear effects. These models can then provide oscillation experiments with reliable predictions of not only visible energy predictions but also signal and background rates. Next-generation long-baseline oscillation experiments are proposing to use argon-based neutrino detectors. The MINERvA measurements on nuclei both heavier and lighter that argon will certainly provide important constraints on reactions on argon itself, but getting a detailed look at what happens very close to the neutrino interaction point is only possible with an active argon target such as a fine-grained time projection chamber.

In this paper we discuss a proposed upgrade which would incorporate the CAPTAIN detector, a 5-ton liquid argon time projection chamber, into MINERvA. MINERvA alone has the capability to measure inclusive cross section ratios between lead and iron to scintillator at the few percent level as described in a companion document to this one; adding CAPTAIN will not only add a new nucleus to compare to scintillator but will also add capability to do high statistics direct comparisons of exclusive processes and activity near the neutrino event vertex. Having both MINERvA and CAPTAIN data will clearly map out nuclear effects from simple to complex nuclei and pave the road to precision neutrino oscillation measurements. Furthermore, the large sample of medium-energy neutrino interactions in CAPTAIN will be useful for validating and studying event reconstruction and particle identification methods for a next-generation liquid-argon detector. This document starts by describing the current state of neutrino interaction uncertainties and a discussion of the physics that would be accessible with this program. The expected performance of the CAPTAIN detector when placed at two different locations within MINERvA is described, with a prediction for event rates of different categories. The technical issues associated with installing and operating the CAPTAIN detector are described, as well as a discussion of what safety issues would need to be addressed. The document concludes with a description of the collaboration management and a proposed schedule for taking data. The technical issues are either similar to those that have already been solved for the MicroBooNE experiment, or will need to be solved to operate a liquid argon detector in any underground location.

2 Introduction

It is well known that neutrinos propagate as a superposition of mass eigenstates and interact as a flavor eigenstates, resulting in the phenomena of neutrino oscillations. Because the neutrino oscillation probability is energy-dependent, reconstruction of the incoming neutrino energy is critical. Experiments that study neutrino oscillations must reconstruct the neutrino energy based only on the final state particles. Therefore, precision measurements of neutrino cross sections are needed in order to have a complete understanding of neutrino oscillations. The next-generation long-baseline neutrino oscillation experiment hosted at Fermilab (formerly LBNE [1], currently being reformulated as the Experiment at the Long-Baseline Neutrino Facility, or ELBNF) has proposed to use a liquid argon time project chamber (TPC) to measure neutrino oscillations at a baseline of 1300 km. At that baseline, the first oscillation maximum occurs in the neutrino energy range from 1.5 to 5 GeV, and most of the electron neutrino appearance signal will be in this energy range. Measurements of neutrino-argon cross sections in this energy range are crucial for the success of the long-baseline program. The CAPTAIN-MINERvA experiment is designed to address this issue. This paper describes a proposal to install CAPTAIN, a small liquid argon TPC, in the MINERvA detector and use the combined data set to study neutrino-argon interactions and liquid argon event reconstruction in the few-GeV neutrino energy range.

The MINERvA experiment is currently taking data in the NuMI beamline, a broadband muon neutrino beam with an energy range spanning 3-8 GeV. This energy range is ideal in that it covers the first oscillation maximum for the future long-baseline neutrino oscillation program [1] and can provide access to both elastic and inelastic processes. The MINERvA detector consists of a series of nuclear targets followed by a fine-grained scintillator tracking region surrounded by electromagnetic and hadronic calorimeters. The magnetized MINOS near detector (ND) serves as a downstream muon spectrometer. MINERvA's dataset includes interactions on a variety of nuclei ranging from helium to lead. The high intensity of the beam means that with the planned neutrino and antineutrino beam exposure, MINERvA will collect several million neutrino charged current (CC) interactions and expects to have the statistics to measure cross section ratios between graphite, iron, lead and the plastic scintillator from intermediate to high $x_{Bjorken}$ at the few percent level. The fine granularity of the MINERvA detector can also provide cross section ratios for individual neutrino interaction channels, such as coherent and inclusive pion production and quasi-elastic scattering.

CAPTAIN (Cryogenic Apparatus for Precision Tests of Argon Interactions with Neutrinos) is a liquid argon TPC currently being built at Los Alamos National Laboratory (LANL) [2]. There are currently 18 US institutions involved in the CAPTAIN collaboration. The CAPTAIN program consists of a prototype detector, mini-CAPTAIN, and the full CAPTAIN detector. The CAPTAIN detector is a portable and evacuable cryostat that can hold 7700 liters of liquid argon. The active volume will be five tons. The CAPTAIN TPC is a hexagonal shape with a 1 m height and 2 m diameter, consisting of three active wire planes with 3 mm pitch and 3 mm wire spacing besides the cathode plane, grid plane, and ground plane. CAPTAIN will be equipped with a photon detection system consisting of 24 phototubes mounted in the cryostat to observe scintillation light produced inside the liquid argon. A laser calibration will be employed to monitor the electron lifetime and drift velocity, as well as measure the electric field in-situ. The mini-CAPTAIN detector is a smaller liquid argon TPC inside a 1500 liter cryostat. At the present time, the mini-CAPTAIN detector is being commissioned at LANL. Mini-CAPTAIN has been successfully filled with liquid argon and cooled, and the electronics, DAQ, purification system, and laser calibration system are all being tested. The CAPTAIN cryostat arrived at LANL in August of 2014, and construction of the CAPTAIN detector will begin in 2015.

CAPTAIN is designed to conduct studies important for precision measurements of neutrino oscillations and observation of supernova burst neutrinos in a next-generation liquid argon neutrino detector. The first major physics run of CAPTAIN will take place at the Los Alamos Neutron Science Center (LANSCE). The neutron data will be used to measure spallation products that are backgrounds to measurements of supernova burst neutrinos and to study events that mimic the electron neutrino appearance signal in a long-baseline neutrino oscillation experiment. Another physics goal is to measure neutrino-argon cross sections at a neutrino energy similar to that of supernova burst neutrinos. The final physics goal of CAPTAIN is the one relevant to the CAPTAIN-MINERvA proposal: to study neutrino interactions in the neutrino energy range relevant for long-baseline neutrino oscillation physics.

Integrating CAPTAIN into MINERvA presents the opportunity to reconfigure the MINERvA detector while keeping with MINERvA's physics mission. Combining CAPTAIN and MINERvA is beneficial because some particles exiting CAPTAIN, most importantly forward-going muons, can be tracked and their energy measured in MINERvA and/or the MINOS near detector, resulting in a far better estimate of the incoming neutrino energy than could be achieved with CAPTAIN alone. In addition, by making measurements of cross section ratios, namely argon to hydrocarbon in the scintillator, stringent tests of the nuclear effect models can be made, since these cross section ratios are not hampered by large flux uncertainties.

We are considering two different ways to integrate the CAPTAIN detector into MINERvA. One possibility is to simply replace MINERvA's existing liquid helium target with the CAPTAIN detector. Depending on the timing of the run, it would also be possible to remove MINERvA's nuclear targets and some of the scintillator planes from the tracking region to place CAPTAIN closer to the MINOS ND, resulting in better muon acceptance. This second option would only be considered once MINERvA has collected sufficient statistics to fulfill its physics goals in the NuMI antineutrino beam mode.

3 The CAPTAIN-MINERvA Program

3.1 Liquid Argon TPC R&D

The data taken by CAPTAIN-MINERvA can be used to validate the liquid argon detector technology in a neutrino beam similar to that which will be used in the long-baseline program. The capabilities for exclusive particle reconstruction and identification and shower reconstruction will be assessed.

Results on neutrino-argon interactions [3, 4, 5, 6] have been released from ArgoNeuT, a 170 liter (0.25 ton active volume) liquid argon TPC that took data in the NuMI low-energy beam configuration. However these results are statistically limited. With a fiducial mass approximately 20 times larger than that of ArgoNeuT, CAPTAIN will collect significantly more events and have better containment of the final state particles. Furthermore, cross section ratio measurements (argon to hydrocaron) are available given the placement of CAPTAIN in front of MINERvA.

Liquid argon TPCs provide excellent position resolution, energy resolution, and particle identification, enabling precision reconstruction of complex interaction topologies. Figure 1 shows one event collected by the ArgoNeuT detector [7]. The individual particle tracks and location of the vertex are easily discernible. Events in the CAPTAIN detector are expected to be of the same high quality, making CAPTAIN a very capable vertex detector for CAPTAIN-MINERvA.

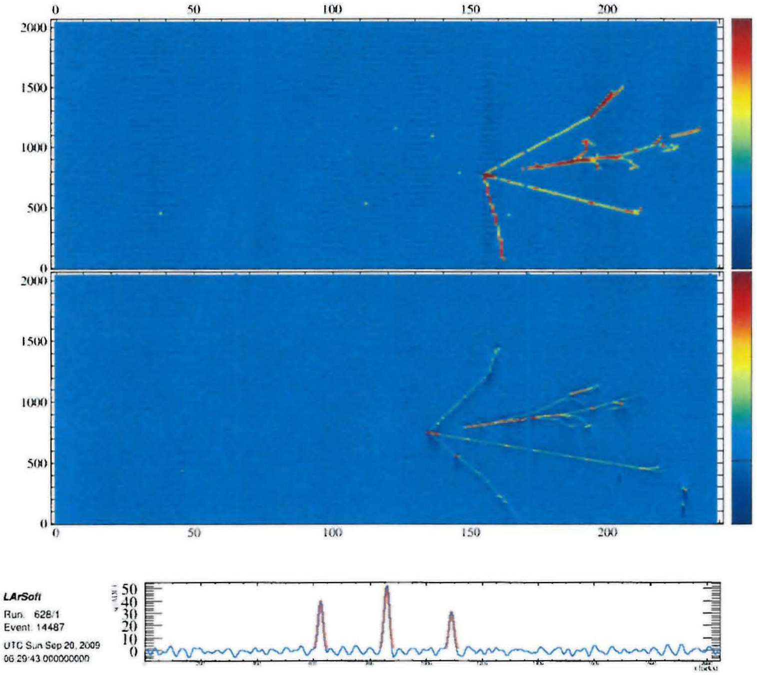

Figure 1: An event display from a real event in the ArgoNeuT detector. The image depicts both the Collection (top) and Induction (bottom) plane views. The horizontal axis corresponds to the wire number within a plane, while the vertical axis corresponds to the sampling time (which is equivalent to the distance along the drift direction). The color-scale depicts the amplitude of the ADC pulse on a wire.

MicroBooNE[8], a 170-ton liquid argon TPC ($\sim$100-ton active volume) which recently completed construction at Fermilab, will study neutrino interactions on argon in the Booster Neutrino Beam (BNB) at Fermilab. The BNB has a neutrino energy $\mathcal{O}(1\text{ GeV})$, consistent with the energy range of the second oscillation maximum for a baseline of 1300 km. Thus measurements made by CAPTAIN in the NuMI beam are complementary to the low-energy neutrino measurements that will be made by MicroBooNE in the BNB. Figure 2 compares the neutrino spectrum from the medium-energy NuMI beam, the BNB, and the proposed flux for LBNE. Figure 2 also shows the cross section for CC neutrino-argon interactions, which are dominated by pion production and Deep Inelastic Scattering (DIS), as defined by the neutrino event generator GENIE [9], in the energy range relevant for ELBNF. Simulations indicate that approximately 87% of all neutrino interactions in CAPTAIN-MINERvA will be pion production or DIS; in MicroBooNE, approximately 60% of the interactions will be quasi-elastic. Therefore CAPTAIN-MINERvA will have the unique ability to study event reconstruction for a large sample of neutrino events with significant particle multiplicities.

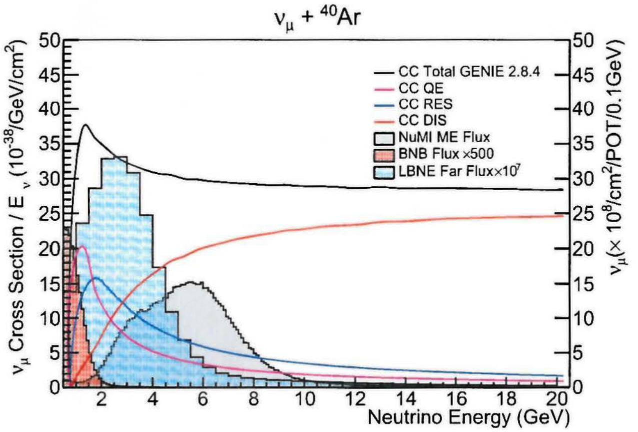

Figure 2: Unoscillated ν_μ LBNE far flux, BNB flux, ME NuMI flux and GENIE cross section on ^{40}Ar.

3.2 Physics Issues

3.2.1 Relationship to the Long-Baseline Program

Recent neutrino oscillation results have shown that one of the main systematic uncertainties is the uncertainty of the neutrino interaction model used to predict the neutrino interaction rate. Even in the case of a carbon target, the uncertainties are rather large despite the number of recent cross section measurements by MiniBooNE, MINERvA, and T2K. On the theoretical side there are, in some cases, large discrepancies between models describing equally well the same experimental results. There is a consensus that more and precise neutrino cross section measurements are needed to constrain the theoretical models.

In contrast, there are only few cross section measurements for argon which is the neutrino target for ELBNF. The goal of ELBNF will be to perform precise measurements of the neutrino oscillation parameters. This requires the precise knowledge of the neutrino interaction cross sections in order to predict both signal and background rates in the far detector. ELBNF will employ near and far detectors which is a standard setup for long baseline neutrino oscillation experiments with the purpose of reducing the flux and cross section systematic uncertainties. The neutrino rate measured in the near detector, before oscillations occur, is used to predict the total neutrino flux at the far detector. However, the flux, illuminating the near detector, is not exactly the same as the one at the far detector, and the detection efficiencies of the near and far detector might be different. Therefore, having a reliable neutrino interaction model is key for the success of ELBNF. Models in modern neutrino generators are constrained by available neutrino and charged lepton data. These include data on various targets including hydrogen, deuterium, iron, lead, water, mineral oil, plastic scintillator, etc. Charged lepton data is used to constrain the vector current while the neutrino data is used to constrain the axial part of the interaction. In addition, pion scattering data is used to constrain the final state interactions (FSI). Given the lack of precise nuclear cross section ratios above and below argon, it has not been demonstrated that existing cross section models can be reliably extrapolated for scattering on argon. The CAPTAIN detector exposed to the NuMI neutrino beam at Fermilab can be used to map out the phase space of neutrino interactions on argon for energies covering the first oscillation maximum for ELBNF. A summary of existing data and theoretical models follows.

3.2.2 Existing Data

The energy range of ELBNF overlaps a variety of experiments. For neutrino probes, MiniBooNE has published a number of interesting results for CH_2 at $\langle E_\nu \rangle \sim 1$ GeV [10, 11]. T2K will add many results for CH and H_2O in the near future. At higher energies ($\langle E_\nu \rangle \sim 4$ GeV), MINERvA has published a few results for CH, Fe, and Pb targets with the NuMI low energy (LE) beam [12, 13, 14] and many more are in progress [15]. ArgoNeuT is starting to publish results for Ar with the same beam as MINERvA, and NOMAD [16] has a set of results at higher energies. These experiments give results for quasielastic (QE), pion production (1π), coherent (COH), and inclusive (INC) interactions. Electron scattering has a wide range of data for inclusive interactions, $(e, e'X)$, for many targets and beam energies. Typical targets of interest for Ar experiments include C, Ca, and Fe including a small data set for Ar. There is a smaller body of data for $(e, e'p)$ and some very new results for $(e, e'pp)$.

A new experiment will take $(e, e'p)$ data for Ar an target soon.

Electron scattering experiments study the vector interaction, i.e. photon exchange, with great accuracy and specificity. The beam energy is fixed and absolute cross sections with few percent accuracy are standard. Experiments to date have emphasized the electron in coincidence with 0-2 hadrons using narrow or wide range spectrometers. Neutrino experiments study a combination of vector and axial vector (i.e. $W^{\pm}, Z^0$) exchange interactions. They use a wide-band beam with $\sim$ 1 GeV width and absolutely normalized results require extensive efforts because the beam is difficult to monitor. In contrast to electron experiments, the neutrino target and detector are almost always identical and the solid angle is then very large (including final state particles at lab angle of $0°$ which is impossible in most experiments). The electron experiments are important to establish nuclear models and FSI of particular particles, but give minimal information about the complex final states neutrino experiments need to understand to accurately measure the neutrino energy.

Event generator Monte Carlo programs must use both kinds of information. The general strategy is to use conserved vector current (CVC) symmetry to transform the electron scattering results into the vector contribution for neutrino scattering. The difference between that and the actual neutrino data is then due to axial vector exchange. Hadron beam data provide the information for FSI of the hadrons produced in neutrino experiments. Thus, electron and hadron beam experiments all have a key role in the prediction of neutrino interactions.

Putting together these disparate pieces of information within existing models is a very difficult task. Estimates of errors associated with these methods are very important but necessarily imperfect. The first priority is to get more and better neutrino data to test extrapolations of nuclear effects to nuclei heavier than argon, and the second priority is to minimize the extrapolations by making measurements on argon in the ELBNF energy range.

3.2.3 Examples of Present Data and Model Problems

Pion Production and FSI from Δ Resonance Excitation One of the most important final states is inclusive one-pion production. This is an important component of the ELBNF first oscillation maximum. The theory for electromagnetic probes is well established from interpretations of pion and photon data. The medium effects of the Δ are known to change cross sections by roughly 20%. Theorists then apply the same models to neutrino data, adding the weak interaction in an analogous fashion.

The MiniBooNE data [10] set a new standard for high quality. The BNB beam is well understood and the statistics are very high. Although they supply double differential cross sections in e.g. pion energy and angle, the most interesting spectrum has turned out to be the one dimensional pion energy spectrum. Since this spectrum overlaps the pion energies coming from the full width of the $\Delta(1232)$ resonance, a strong FSI effect is expected with the strongest suppression at $T_\pi \sim 160$ MeV where the π^+C cross section peaks. Rodrigues [17] reported comparisons with theoretical calculations and event generator results. The surprising result was that none of the calculations were in good agreement and the best theoretical calculations (GiBUU [18] and Valencia [19]) had the poorest match to the data. The conclusion is that either the pion beam data is not the proper way to build an FSI model or that the models are wrong.

The MINERvA data [15] has a significant overlap with the MiniBooNE kinematics; they present both energy and angle spectra for events where $W < 1.4$ GeV. This focuses on events where a $\Delta(1232)$ resonance was created at the principal vertex. The newer data shows that the pion energy spectrum is more valuable than the angle spectrum. Like MiniBooNE, there is no dip at the peak of the resonance. Some calculations (NuWro [20], NEUT [21]) are in good agreement while others (GENIE [9], GiBUU [22]) have the right shape but the wrong absolute magnitude. Equality of the MINERvA and MiniBooNE cross sections for high energy pions ($T_\pi > 300$ MeV) despite the significant difference in average neutrino energy strongly implies a problem with relative normalization of the two experiments.

This is the odd situation where two experiments don't have a common interpretation. Calculations have different problems in describing each data set. Oscillation experiments are forced to cope with this and application of significant systematic errors is the expected result.

Pion Production at Higher Mass For higher W, behavior of higher energy pions with higher multiplicity is studied. The reaction mechanism is more complicated and the kinematical region 1.8 GeV $< W <$ 2.3 GeV is called the transition region. It sits between resonance-dominated and DIS regions and shares characteristics of each of them. There is a wealth of data from electron experiments for a wide range of kinematics and target. For nuclear targets, (e, e') data is most important although a new result for inclusive pion electroproduction at JLAB is expected soon. For nucleon targets, the Δ excitation dominates at $Q^2 <\sim 1$ GeV^2. At higher W, a tower of the higher mass resonances is seen but nonresonant mechanisms are of comparable strength. Similar behavior is seen in the low statistics deuterium bubble chamber data with neutrino probes. Above $W > 1.8$ GeV, empirical approaches such as KNO [23] become appropriate. This is the model chosen in GENIE [24]. There is very little neutrino data for nuclear targets for this range of excitation. Although older data has been valuable for model development, new MINERvA data with the medium-energy NuMI beam will be a much-needed addition.

Deep Inelastic Processes At even higher excitation energies $W > 2$ GeV, the relevant processes come from interactions with the quarks in the target. DIS accounts for about a third of all neutrino interactions at the neutrino energy of the first oscillation maximum for ELBNF and becomes the dominant interaction channel at neutrino energies above 5 GeV. DIS has been measured on various targets with high precision for neutrino energies $E_\nu > 10$ GeV. In this region the neutrino DIS cross section has been measured on carbon, iron and lead targets with a precision better than 4% by the CDHS [25], NuTeV [26], NOMAD [27], and CHORUS [28] experiments. At these energies most of the phase space is in the regime of perturbative QCD. Higher order corrections like target mass (TM) effects and higher twist (HT) are needed at high $x_{Bjorken}$ and low Q^2. The Bodek-Yang [29] model is used to simulate neutrino DIS events in modern neutrino generators. This model is based on the leading order (LO) parton distribution functions (PDF) for the quark densities in a free nucleon, and includes next-to-leading order (NLO) corrections. The free nucleon PDFs are obtained from a global fit to the charged lepton DIS data. GENIE uses a hadronization model to predict the multiplicity of the initial state. This model is tuned to the existing multiplicity data and bubble chamber data. The hadronization model also includes heavy quark production. Final state interactions modify the multiplicities for scattering on nuclei. Nuclear effects have been measured by charged lepton DIS experiments with high precision. However, data from NuTeV and CHORUS suggests differences between neutrino and charged lepton DIS due to the axial-vector current and to flavor selection which results in almost no enhancement in the shadowing region (small $x_{Bjorken}$) for neutrino scattering. The MINERvA experiment will measure the nuclear dependence for neutrino and antineutrino DIS as ratios to carbon Fe/C and Pb/C. In the energy region $E_\nu < 10$ GeV and $W < 4$ GeV the majority of DIS events have low multiplicity which is then modified by FSIs. In this part of phase space the coverage by existing data is poor which results in higher systematic uncertainties on the hadronization model. MINERvA will measure the neutrino and antineutrino DIS cross sections in this region on C, Fe and Pb.

3.2.4 What do we know about νAr interactions?

The ν-nucleus interaction is very weak. Therefore, the principal interaction of the neutrino should occur according to the density of the target particles. The total CC cross section is proportional to the sum of the interactions with the constituents. For example, Fe and C $\sigma_{CC,tot}$ cross sections divided by A are often plotted together; the Fe cross sections get an isoscalar correction of a few percent. On the other hand, the remainder of each event is dictated by strong interactions which have a mean free path of a few fm or less. These interactions have important energy dependence due to the $\Delta(1232)$ nucleon resonance having a very important role in many studies. Therefore, the hadron-nucleus total reaction cross section σ_{reac} depends on $A^{\frac{2}{3}}$ and the FSI make important modifications to the simple picture. Depending on the variable examined, the A dependence varies significantly. Final states involving pion production will scale more like $A^{\frac{2}{3}}$, but we need data to know for sure. Events from Ar will have the energy from the principal interaction divided in more ways, higher multiplicity and more low energy nucleons, which will provide a challenge to any detector. In addition, the target constituents have properties that are modified by the nuclear environment. Impulse approximation (neutrino interacts with a single nucleon) prediction for the total QE cross section at $\langle E_\nu \rangle \sim 1$ GeV are well below the MiniBooNE data. The leading explanation is that the neutrino sometimes interacts with correlated nucleons. Theoreticians predict this component of the total cross section is proportional to A, but support from data is not well established. At higher energies, the EMC effect shows that dividing the total cross section into bins of x shows regions where different physics processes are important and the Fe and ^{2}H data don't have simple scaling.

ν-nucleus interaction event generators (e.g. GENIE, NuWro, and NEUT) incorporate models for all these processes. Although these models are simplified versions of the leading theoretical models, this allows predictions for all processes at all energies for all nuclei. At this time, they rely on the impulse approximation for all interactions and the Fermi Gas nuclear model. However, the model developers have had a lot of interaction with theorists to gain access to more sophisticated models. These are now going into the codes.

Therefore, event generator predictions for νAr are based on interpolations and extrapolations of simplified models. Because of the simple scaling effects described above, basic quantities are nevertheless consistently predicted with moderate accuracy. Although the effect of these approximations is sometimes known and able to be incorporated into a systematic error, there are notable exceptions, as seen in the examples in the previous subsection. The interplay of data and model remains an interesting subject.

Although the accuracy of any prediction depends on many factors, a rough guide comes primarily from the quality of underlying data and models. The total CC cross section for νAr can be reliably predicted. On the other hand, detailed information such as neutral energy and proton multiplicity distributions will prove to be more difficult.

The generator studies at the NUINT conferences have studied consistency among models. The NUINT09 study [30] showed wide variations in some cases and surprising agreement in others. The predictions for the pion kinetic energy distribution in single pion production from ν_μC at 1 GeV (See Fig. 3 left) showed wide variation due to many effects. Predictions for the total CCQE cross section for ν_μC (See Fig. 3 right) are all in agreement because the impulse approximation and the Llewellyn-Smith $\nu_\mu N$ interaction were used by all models. Confrontation with MiniBooNE data showed all were wrong. On the other hand, more detailed distributions such as the proton kinetic energy showed wide variations. These predictions were before the release of the MiniBooNE data. Some models were then tuned to the data and others remain in disagreement with it.

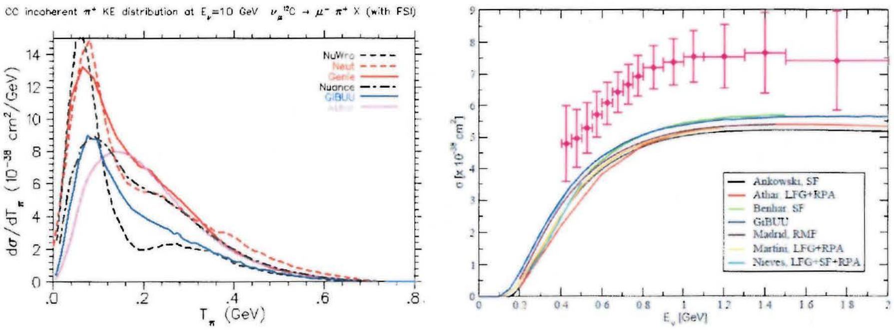

Figure 3: Results of the NUINT09 theory study. Left: Pion kinetic energy cross section for 1 Gev ν_μC. Data comes from MiniBooNE and authors of the calculations are shown. Calculations in recent comparisons with MiniBooNE and MINERvA data show significant changes. Right: Predictions for CCQE total cross section for ν_μC. This was before the realization that nucleon correlations (commonly called MEC or *npnh*) can have significant contribution. Figure was constructed by Luis Alvarez-Ruso using the NUINT09 theory study.

At NUINT12, the studies were suggested by experimental collaborations and ν_μAr studies as preparation for ELBNF were prominent. Fig. 4 shows two results [31] from that study, both for ν_μAr for 3 GeV neutrinos. The proton multiplicity shows the end result of various principal interactions followed by FSI. The total visible energy sums total energies of lepton and mesons and kinetic energy of protons. The significant differences would bring problems for any ELBNF analysis as this is a key ingredient in measurement of the incident neutrino energy. Any deviation from 3 GeV must be measured via neutral particles or come from the simulation.

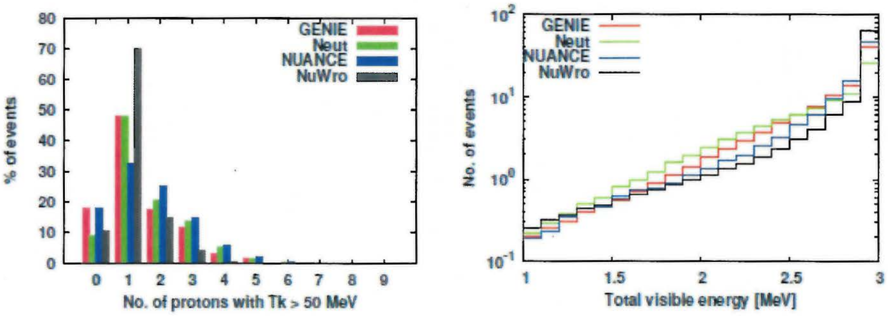

Figure 4: Predictions of various event generators for $\nu_\mu Ar$ for 3 GeV neutrino beam energy from the NUINT12 study. Left: Proton multiplicity for proton kinetic energy greater than 50 MeV. Right: Total visible energy.

We see that event generators will always be behind theoretical understanding and theoretical understanding will always be behind experiment. At the same time, predictions from theory based on results from other probes sometimes anticipate experimental results. Although we expect qualitative agreement in the key quantities from existing event generators, that is not sufficient for assessing the needs for precision experiments such as ELBNF now in the planning stages. The CAPTAIN-MINERvA experiment will allow the most accurate tuning of event generators for the best ELBNF performance.

3.3 Expected Performance

Simulations of the CAPTAIN detector geometry in the on-axis medium-energy NuMI flux predict a 25% containment efficiency of CAPTAIN alone, where containment includes all outgoing particles except leptons and neutrons. By this definition, we estimate 250k contained events per 10^{20} protons-on-target (POT). Thus, in one year, we could collect up to 1.5M contained events, assuming the full power of the NuMI beam.

To study the acceptance of CC events in the MINOS ND, neutrino interactions were generated uniformly in the CAPTAIN TPC with GENIE 2.8.4 and outgoing muons were tracked in MINERvA and MINOS using GEANT4 [32, 33]. The incoming neutrino energy distribution for CC events is shown on the left in Figure 5; the muon energy is shown on the right.

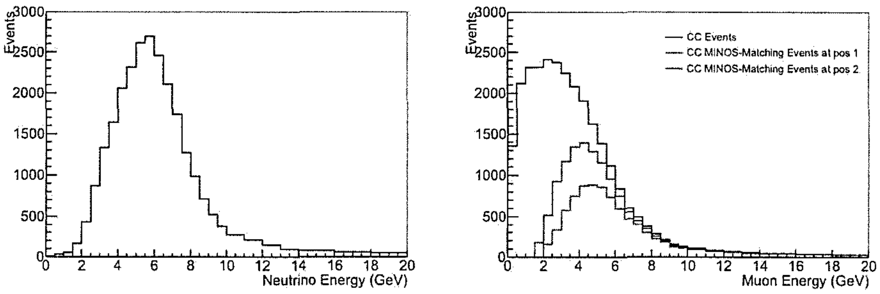

Figure 5: Left: Incoming neutrino energy for CC events in the NuMI ME flux configuration. Right: Muon energy for CC events. (Red) CC events with momentum and charge reconstruction assuming CAPTAIN at position 1. (Blue) CC events with momentum and charge reconstruction assuming CAPTAIN at position 2.

As was mentioned previously there are two possible locations for the CAPTAIN detector with respect to the MINERvA detector, at the current position of the helium target (position 1) or in the upstream part of tracker region (position 2). The magnetized MINOS ND can provide the measurements of muon momentum and the sign of the muon charge for events where the muon reaches MINOS ND. This matching criterion is based on a reconstructed muon track that exits CAPTAIN, exits the back of the MINERvA detector and reaches the MINOS ND. If the muon is reconstructed in the MINOS ND, the muon momentum is measured by the MINOS ND from the track curvature or its range depending on whether the muon stops in the MINOS ND. A detailed study by MINERvA shows that the total muon momentum uncertainty for muons is 2-3% for the curvature-based measurement relative to the range-based measurement [34]. For CC events with a fully reconstructed muon, Figure 6 shows the acceptance as a function of neutrino energy, muon energy, Q^2 and muon angle.

Reconstructing the incoming neutrino energy is crucial in order to measure oscillation parameters. One of the key factors in neutrino energy reconstruction is detector containment. The containment efficiency from stand-alone CAPTAIN simulations was combined with MINOS muon matching acceptance to estimate the statistics for

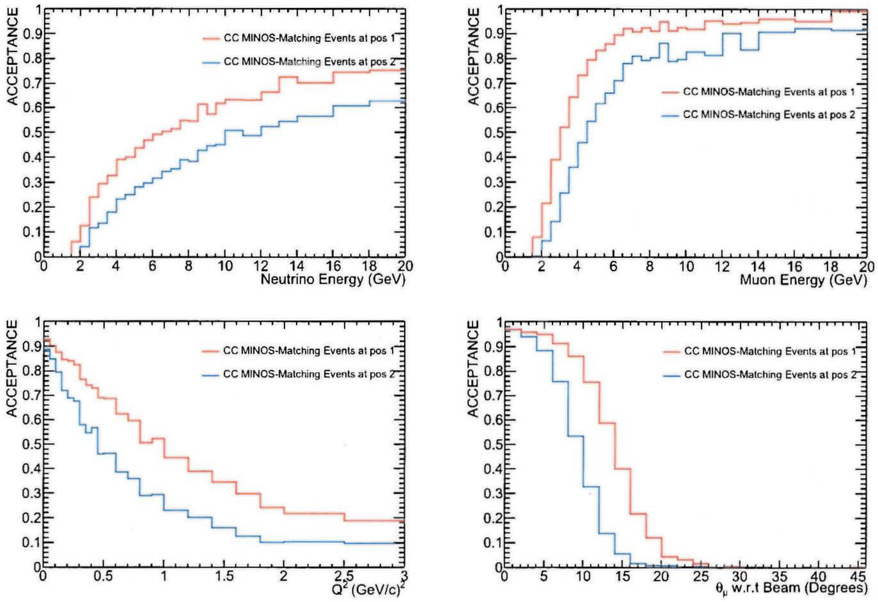

Figure 6: Muon acceptance for CC events as function of neutrino energy, muon energy, Q^2 and muon angle with respect to the beam direction.

various measurements. Table 1 shows the efficiency and acceptance for CCQE-like events ($\nu_\mu + ^{40}Ar \rightarrow \mu^- + Np$ and no mesons, N can be any number of protons), CC $1\pi^\pm$ ($\nu_\mu + ^{40}Ar \rightarrow \mu^- + \pi^\pm + X$) and CC $1\pi^0$ ($\nu_\mu + ^{40}Ar \rightarrow \mu^- + \pi^0 + X$).

	Contained Events in CAPTAIN	Contained Events in CAPTAIN at pos 1 w/MINOS Match	Contained Events in CAPTAIN at pos 2 w/MINOS Match
CCQE-like	488,250	255,354	339,333
$CC1\pi^\pm$	191,250	59,478	88,930
$CC1\pi^0$	189,000	48,384	76,167

Table 1: Contained efficiency for CC events with a reconstructed muon using MINOS ND, assuming 6×10^{20} POT exposure.

4 Technical Details

4.1 Relative Sizes of Detectors

The CAPTAIN detector is of a comparable fiducial mass to that of the inner tracking region of the MINERvA detector, so the statistical uncertainties for both samples are comparable.

Figure 7 shows one potential location for the CAPTAIN detector: in this case the nuclear target region of the MINERvA detector has been removed but most of the scintillator target is still in place.

Figure 8 shows the relative sizes of the CAPTAIN and MINERvA detectors as seen by the neutrino beam.

It is clear from these two diagrams that the CAPTAIN detector would fit conveniently in front of the MINERvA detector and could be supported from below to be centered on the neutrino beam.

The ultimate location of the CAPTAIN detector depends on whether or not the nuclear target region of the MINERvA detector is unstacked but most of the technical challenges associated with installing and operating the CAPTAIN detector underground are independent of the details of that location.

The MINOS shaft through which all equipment must pass to be installed underground is roughly half of a cylinder that is 22 feet in diameter as shown in Figure 9. The 15-ton capacity crane that operates in the shaft is adequate to lower the vessel,

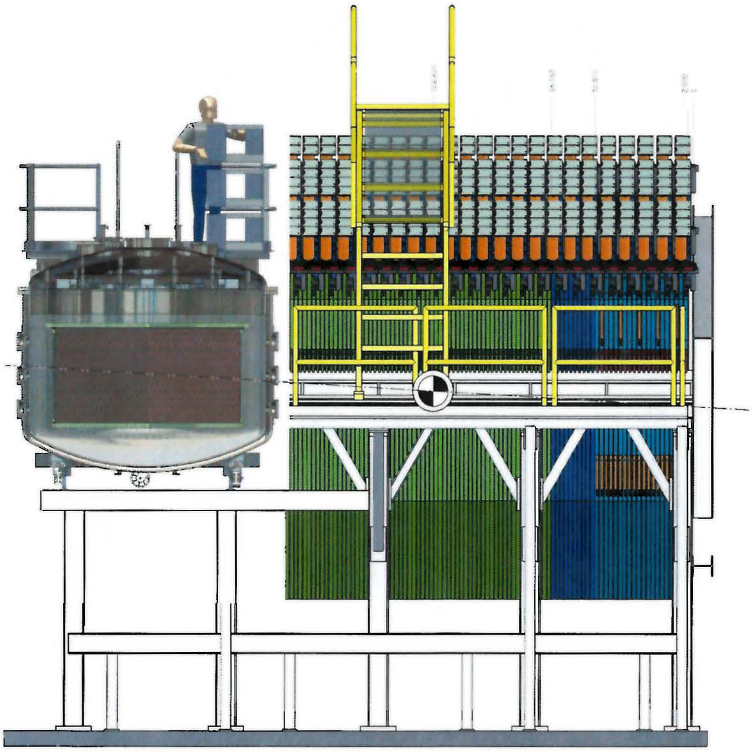

Figure 7: Relative size and possible location of the CAPTAIN detector in front of the MINERvA detector. The neutrino beam travels from left to right at an angle of 58 mrad to the horizontal.

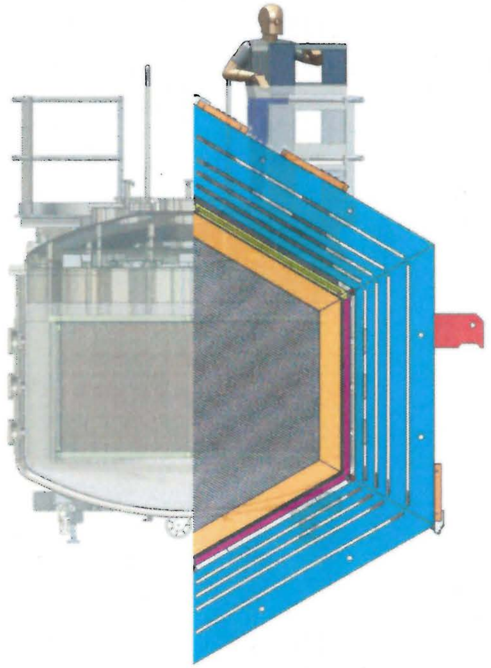

Figure 8: Relative transverse sizes of the CAPTAIN and MINERvA detectors, as seen from the incoming neutrino beam.

which when empty weighs 5 tons. A cart will need to be built to accept the vessel when it reaches the lower level, and the cart can be pulled using the same fork-truck by which the MINOS and MINERvA detectors were installed.

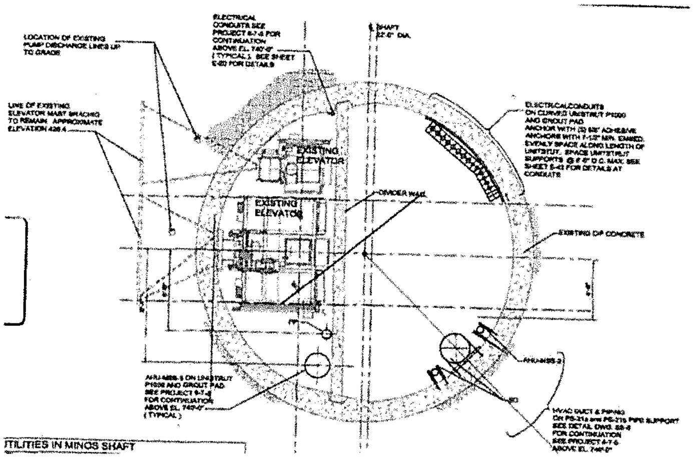

Figure 9: Drawing of the MINOS shaft, dimensions are in feet.

4.2 Operations Requirements

In order to cool and then fill the CAPTAIN cryotarget the vessel will need access to a 2000 liter dewar of liquid nitrogen and a 10000 liter dewar of liquid argon, respectively. These two large dewars would need to be located above ground, next to the MINOS Surface building. Two lines of vacuum-jacketed pipe approximately 2 inches in diameter would need to be run from the dewars above ground to the final detector location, these would be approximately 700 feet long each. There is currently adequate space in the shaft for these lines.

The CAPTAIN detector will need to be operable remotely since staffing two people on shift underground 24/7 is prohibitive due to the small size of the joint CAPTAIN-MINERvA collaboration. During the Los Alamos running the CAPTAIN detector's cryogenic control system is not remote, so that upgrade will be an important cost of running CAPTAIN in the NuMI beamline. A smaller version of the MicroBooNE cryogenic control system would be appropriate for this (given the smaller volume of liquid argon that is supported).

4.3 Safety Issues

The largest safety issue associated with CAPTAIN-MINERvA is the fact that this volume of liquid argon represents a significant oxygen deficiency hazard (ODH) if for some reason the vessel were to leak catastrophically. Because of the relative density of argon to oxygen, the oxygen in the underground cavern would relatively quickly be displaced.

The solutions to mitigate this hazard are already being examined in the context of the ELBNF liquid argon operations, and involve careful containment and then venting of any potentially spilled argon. There is currently a 19-inch diameter shaft in the downstream end of the Near Detector hall; that shaft could be part of the venting system in addition to the upstream shaft. Nevertheless it is likely that people working underground would need to bring supplies of oxygen with them, and the area would no longer be classified as an ODH class 0 enclosure. These restrictions are not unprecedented either at this laboratory or at other laboratories worldwide, and are not seen as prohibitive.

5 Collaboration Management

The physics goals described in this LOI are of interest to both the current CAPTAIN and MINERvA collaborations, and the effort needed to achieve these goals is larger than either current collaboration could supply. Therefore we plan for members of each of the two current collaborations to join together as one new collaboration, and the data taken by both detectors (and the MINOS near detector) would be readily accessible to all members of the new collaboration. For the moment this new experiment is called CAPTAIN-MINERvA.

Similarly, the reconstruction of events would have to combine information from up to three detectors, in addition to the neutrino beamline information, therefore the reconstruction software for all three detectors needs to be shared throughout the entire collaboration.

This new collaboration would make use of existing infrastructure from the current MINERvA and CAPTAIN experiments (document data bases, simulation packages, etc) until such time that it makes sense to merge that infrastructure into one new platform.

6 Proposed Schedule

The schedule for the CAPTAIN-MINERvA project depends on several factors. The first is the availability of the CAPTAIN detector. CAPTAIN will take data in a neutron beam at LANSCE in 2015-16. Therefore the earliest date that CAPTAIN could be moved to Fermilab is sometime in 2016.

A separate LOI is being submitted to place CAPTAIN in an off-axis position in the BNB at Fermilab to study neutrino-argon interactions in the few-MeV energy region, important for detection of supernova bursts in ELBNF. A new building would be constructed near the BNB target hall to hold the CAPTAIN detector. Ideally, we would like to run both CAPTAIN-MINERvA and CAPTAIN-BNB on a time scale such that they can both provide useful input for ELBNF.

The start date of the CAPTAIN-MINERvA and CAPTAIN-BNB programs both depend on the installation of necessary infrastructure at Fermilab. For CAPTAIN-MINERvA to run in the underground MINOS hall, the ODH calculations and system must be put in place, a new ventilation system and plumbing must be installed, and new controls for remote running must be implemented. For CAPTAIN-BNB to run, neutron measurements must be made to determine the exact location and necessary shielding for the CAPTAIN-BNB structure, and then the structure must be built. Before any of this can take place, sufficient time must be allowed for engineering effort and costing of the new infrastructure. To meet the schedules proposed in this section, the required engineering for both projects would ideally begin in 2015.

Another critical factor for the schedule is the availability of the NuMI beam. Our understanding is that both the NuMI beam and the BNB will operate until at least 2021 (NuMI for the NOvA experiment and BNB for MicroBooNE and other short-baseline neutrino projects). Assuming CAPTAIN is moved to Fermilab in 2016, we can expect at minimum five years to complete both the CAPTAIN-MINERvA and CAPTAIN-BNB programs based only on beam availability.

Since NuMI is expected to be running for a sufficient amount of time, a more important factor for CAPTAIN-MINERvA's schedule is the availability of the MINERvA detector and collaboration. The MINERvA collaboration expects to stop operating MINERvA and the MINOS ND after accumulating 12×10^{20} POT in antineutrino mode and 6×10^{20} POT in neutrino mode. When this occurs depends on the NuMI run plan and accelerator and beamline performance, but could be as early as 2018. The CAPTAIN-MINERvA project depends critically on the participation of the MINERvA collaboration in installing the detector, operating the detector, and analyzing the combined data set. Therefore, CAPTAIN-MINERvA data collection should begin by 2018 at the latest. After that date, there likely would not be enough participation from MINERvA collaborators for CAPTAIN-MINERvA to be feasible.

Based on these considerations, we propose two possible schedule scenarios:

- **Scenario A:**
  - CAPTAIN is moved to Fermilab in 2016 and placed in the BNB location. CAPTAIN-BNB takes data in 2016-2018. The CAPTAIN detector is moved to the MINOS near hall, and CAPTAIN-MINERvA operation begins in 2018.
  - **Benefits:** Results from CAPTAIN-BNB could potentially influence the design of the photon detection system for the ELBNF detector, crucial for supernova neutrino detection.
  - **Potential risks:** A delay in moving CAPTAIN to Fermilab (due to delays in CAPTAIN commissioning or the neutron run) could push the start date of CAPTAIN-MINERvA until after MINERvA has shut down, making CAPTAIN-MINERvA no longer feasible.
- **Scenario B:**
  - CAPTAIN is moved to Fermilab in 2016 and installed in MINERvA. CAPTAIN-MINERvA takes data in 2016-2018. The CAPTAIN detector is moved to the BNB location, and CAPTAIN-BNB operation begins in 2018.
  - **Benefits:** More collaborators from MINERvA would be able to participate in CAPTAIN-MINERvA. There is also less risk of the program being delayed until long after MINERvA has shut down. CAPTAIN-MINERvA

could potentially take both antineutrino and neutrino data, depending on the NuMI schedule.

- **Potential risks:** The CAPTAIN-BNB results might too late to be of use in the ELBNF photon detection design, though the cross-section measurements could still be useful in physics studies for ELBNF, and later, data analysis.

The choice of the preferred schedule depends on physics priorities, technical considerations for each project, and availability of people. Due to the complexity of the issues involved, we have not yet chosen a preferred scenario of the two presented above. Discussions among the current members of the CAPTAIN and MINERvA collaborations are ongoing, and we expect to reach a conclusion in the near future.

The dates given above could change depending on a number of factors, including: changes in the NuMI or BNB schedules, a change in MINERvA's expected end date, a delay in CAPTAIN's move to Fermilab, a delay in the construction of the CAPTAIN-BNB building, or a delay in systems necessary to operate CAPTAIN in the MINOS near hall.

7 Summary

In summary, this paper presents a joint proposal from the CAPTAIN and MINERvA collaborations to study neutrino-argon cross-sections and event reconstruction in liquid argon in the neutrino energy range of 1-10 GeV. CAPTAIN-MINERvA would take data for at least 2 years, beginning no earlier than 2016 and no later than 2018. To meet this proposed schedule, the necessary preparations for the MINOS ND hall would need to begin in 2015. CAPTAIN and MINERvA share the goals of studying neutrino and antineutrino interactions that are important for the future long-baseline neutrino oscillation program, and combining the CAPTAIN and MINERvA detectors will expand the physics reach of both experiments in a way that is complementary to existing liquid argon detector R&D efforts.

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