MINERvA and CAPTAIN: Probing the Nucleus with Neutrino Scattering

The MINERvA and CAPTAIN Collaborations

Neutrino-nucleus cross-section measurements are vitally important to neutrino oscillation experiments which must determine the incoming neutrino energy by measuring only the final state particles. The MINERvA experiment is currently studying neutrino interactions on a variety of nuclear targets from helium to lead. Next-generation long-baseline oscillation experiments are proposing to argon-based neutrino detectors. In this paper we discuss the physics goals of the current MINERvA run as well as 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 per cent level; adding CAPTAIN will not only add a new nucleus to compare to scintillator but will also add capability to do high statistics comparisons of exclusive processes. 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.

I. EXECUTIVE SUMMARY

The discovery of neutrino masses and mixings from observations of solar and atmospheric neutrinos has set in motion an ambitious new program of neutrino oscillation measurements. These measurements rely critically on the ability of neutrino detectors made of complex nuclei to identify the energy of an incoming neutrino. In order to estimate that energy in any detector technology, experiments depend on an accurate prediction of the spectra of produced particles that not only are produced in the charged current interaction but that exit the nucleus after final-state interactions. Understanding the convolution of these two processes is a major challenge that requires input from both the nuclear physics and high energy physics communities. The predictions available in neutrino event generators today are frequently based on low-statistics single nucleon cross sections with effective models of how the nuclear environment modifies both the initial- and final-state particles in the interaction.

The most precise constraints on the effect of the nucleus on lepton scattering come from charged-lepton scattering in the deep inelastic regime [1, 2]. The measured ratios of nuclear cross sections to the deuterium cross section are understood, in particular kinematic regions, to be based on the different quark-parton structure of bound nucleons compared to that of free nucleons [3–6]. This suggests that the same ratios measured with neutrino and antineutrino scattering in the DIS regime will give different results since these each access different combinations of the quarks than those accessed by charged leptons. MINERvA will make precision ratio measurements of iron and lead to hydrocarbon, while CAPTAIN will add argon. In addition, these ratios will be measured in kinematic regions below DIS where no theoretical guidance is available, but where neutrino oscillation experiments must operate.

The MINERvA experiment is currently taking data in the NuMI beamline, a broadband muon neutrino beam 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 [7] and can provide access to both elastic and inelastic processes. 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 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.

A future upgrade to the MINERvA physics program is being considered where a fully active liquid argon time projection chamber (TPC), CAPTAIN, would be placed upstream of the MINERvA scintillator target to enable neutrino and antineutrino cross-section ratios between argon and hydrocarbon to be measured. Since CAPTAIN has a similar fiducial mass to the current MINERvA plastic scintillator mass cross sections can be measured with comparable statistical precision. An expected 1M charged current events on argon per year will have contained hadronic systems at the nominal NuMI intensity. In addition, the liquid argon TPC capabilities allow for a detailed study of event topologies and energy deposition in the 0-100 MeV regime to fully investigate the unexpected hadronic final states seen in neutrino quasi-elastic scattering. By combining the MINERvA cross section ratio measurements with CAPTAIN MINERvA measurements of the ratio of argon to hydrocarbon, a more complete picture of the nuclear environment can emerge. This new picture will guide models needed for the precision oscillation measurements of the current and next generation of long-baseline neutrino experiments.

II. PHYSICS GOALS

Neutrino oscillation measurements rely critically on the ability of neutrino detectors made of complex nuclei to identify both the flavor and energy of the incoming neutrino. While the flavor identification is relatively straightforward through the charged-current interaction, the energy determination is far more challenging. In order to predict the visible energy in any detector technology, experiments depend on an accurate prediction for the spectra of particles that exit a nucleus after a neutrino charged-current interaction for a given incoming neutrino energy. The nuclear effects that will modify those spectra will potentially distort a measurement of neutrino energy spectra in oscillation experiments[8]. This whitepaper describes a new experiment that would combine two high-resolution fully-active detectors: a liquid argon TPC detector followed by a fine-grained scintillator (CH) detector. This combination of detectors would provide a much more complete picture of how the nuclear environment affects neutrino interactions by simultaneously measuring a wide range of exclusive neutrino interactions on both carbon and argon.

Neutrino event generators currently utilize electron scattering experimental data and interpretation to build physics models. Fortunately, the electron beam energies of Jefferson lab are similar to the neutrino beam energies used in oscillation experiments. Besides providing details of the vector response, the electron scattering experiments provide the best description of final-state interactions for both electron and neutrino interactions. Since the incoming electron energy is known, electron beam measurements on complex nuclei have been primarily focused on measuring the scattered electron, sometimes with one hadron. However, neutrino experiments must measure the beam energy from the final state and the event generators must therefore have an accurate description of all of the final state particles. In addition, modern electron scattering experiments emphasize relatively simple nuclei rather than the heavy nuclei used in neutrino detectors, and only neutrinos can measure the weak interaction strength. Therefore, both detailed electron and neutrino cross sections are needed to accurately describe neutrino signals in oscillation experiments.

One of the more interesting issues which has attracted wide attention in the neutrino community is the surprising complexity of the supposedly simple charged-current quasi-elastic (CCQE) scattering when it occurs on nucleons in a nucleus. MINERvA's neutrino CCQE measurement[9] found evidence for additional proton production in quasi-elastic neutrino scattering but not in antineutrino scattering, which could be due to correlated *np* pairs in the nucleus. This had previously been suggested at lower neutrino energies by the MiniBooNE[10] collaboration and by recent direct observation in a small number of events in a liquid argon TPC by the ArgoNeut[11] collaboration. These correlations can both shift the initial nucleon kinematics, leading to distortions in the final state lepton kinematics, and significantly influence the low final state activity one would expect in a quasi-elastic scatter. In particular, the final state activity becomes quite different for neutrinos - where an additional proton might be expected in the final state - than for antineutrinos, where an additional neutron is more likely. Detailed study of event topologies and energy deposition in the 0-100 MeV regime will be necessary to fully validate neutrino interaction models needed to achieve the 2% uncertainties assumed for production rates at future long-baseline measurements[7].

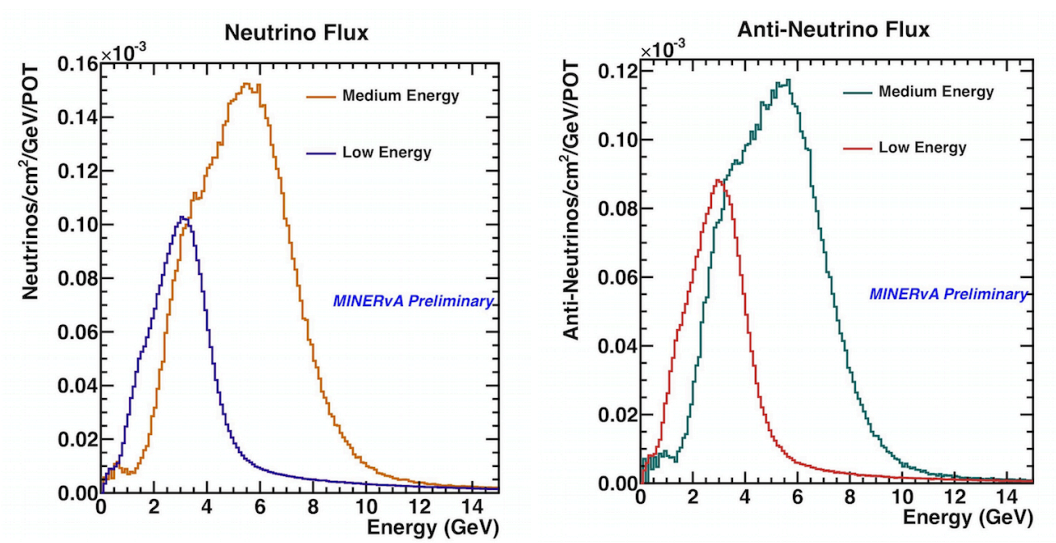

FIG. 1: Neutrino (left) and antineutrino (right) fluxes from the NuMI beams, for both the low energy and medium energy beam configurations. The polarity of the focusing system is reversed to produce the antineutrino beam.

There is currently a large effort underway worldwide to understand neutrinos and their interactions in nuclei to inform measurements of neutrino oscillations. For example, the MINERvA experiment uses the NuMI beamline at Fermilab and between 2010 and 2012 collected a substantial dataset in a neutrino beam with a peak energy of 3.5 GeV (see Fig. 1). It has already published results on exclusive processes on plastic scintillator[9, 12, 13] and on the ratios of inclusive charged-current interactions on carbon, lead and iron compared to scintillator[14]. The experiment is currently running in the medium energy neutrino beam where nuclear effects in deep inelastic neutrino scattering can be probed (also shown in Fig. 1). Electron scattering measurements are also needed for the future neutrino oscillation program: the E02-019 program at JLAB has measured electron scattering off a broad range of nuclei[15], and the CLAS dataset has been used to measure single pion production in electron scattering [16]. These measurements will be further strengthened by the addition of new and upcoming measurements of nuclear effects in $e - A$ DIS (JLab) and Drell-Yan processes (SeaQuest at Fermilab) to provide increased ability to separate both the flavor and the valence/sea dependence of nuclear effects. Most recently there is a proposal, PR12-14-012, accepted at Jefferson Laboratory, to measure the spectral functions on argon[17]. These experiments provide clean inclusive and single pion scattering measurements.

The current MINERvA physics program is taking advantage of the high intensity of the NuMI beam line to map out the different possible nuclear effects that may be present in neutrino scattering but have until now only been predicted or suggested. Figure 2 shows the cross-section ratios between iron and scintillator (left) and lead and scintillator (right) as measured by MINERvA in 3×10^{20} POT in the low energy beam. The data show that as a function of the reconstructed variable $x_{Bjorken}$, which in the quark parton model corresponds to the fractional momentum of the struck quark, the nuclear effects measured are significantly larger than those predicted. The two kinematic regions where the data is not in agreement with the prediction correspond to different channels: the high $x_{Bjorken}$ behavior indicates nuclear effects near the elastic peak, while the low $x_{Bjorken}$ behavior indicates effects that may be present in pion production or deep inelastic scattering. The measurement shown here was limited by the statistics of the low energy run, but the current medium energy run will collect well over a factor of 10 higher statistics in the inclusive channel in neutrino running, and comparable data statistics in the low energy beam. With 6 (12) $\times 10^{20}$ POT in neutrino (antineutrino) mode, MINERvA expects to be able to measure the cross section ratios as a function of $x_{Bjorken}$ with about 10^4 events in each of the bins shown in figure 2, in both neutrino and antineutrino modes.

While the inclusive measurements in the medium energy beam are intriguing, the MINERvA detector's capabilities allow for individual channel cross-section ratios to be measured in the medium energy beam as well. For example, in the low energy data set MINERvA collected some 7 (6) thousand quasi-elastic like events originating in the iron (lead) in which both a proton and muon are identified. In the medium energy dataset, for 6×10^{20} POT in neutrino mode, the same hit-level simulation predicts that MINERvA will collect nearly nine times that amount in each target, allowing for precise cross-section ratio measurements. The quasi-elastic interaction is one of the most important for current and future oscillation experiments, and this will be the first direct comparison of that process between different nuclei.

Another example of an exclusive channel that can be measured on nuclear targets is the coherent charged-current scattering process, where a neutrino interacts with an entire nucleus and in the exchange emits a charged pion and muon. Before MINERvA this process was only seen at higher energies and not seen at experiments around 1 GeV. In the NuMI low energy dataset, in neutrino (antineutrino) mode MINERvA isolated 1628 (770) coherent candidates after background subtraction [18]. In the medium energy beam, for 6 $\times 10^{20}$ POT in both neutrino and antineutrino mode, MINERvA expects to collect a factor of 6 (9) times more data than in the low energy beam. Having these statistics on hydrocarbon implies that cross section ratios between lead or iron and hydrocarbon can be measured to 8% (9%) in neutrinos (antineutrinos).

An experiment that bridges the MINERvA medium energy- and the JLAB argon spectral function- measurements can come from high statistics measurements of neutrino and antineutrino interactions on both argon and scintillator in the NuMI medium energy beam. This can be achieved by combining the CAPTAIN and MINERvA detectors. CAPTAIN (Cryogenic Apparatus for Precision Tests of Argon Interactions with Neutrinos) is a 5-ton liquid argon time projection chamber (TPC) currently being built at Los Alamos National Laboratory. By taking data in the NuMI beam, CAPTAIN can make high statistics measurements in a broad (anti)neutrino energy range, from the pion production threshold to deep inelastic scattering energies. The fine resolution of the detector will allow detailed studies of low-energy protons that are often invisible in other neutrino detector technologies. In addition, liquid argon TPCs give good separation between pions, protons and muons over a broad momentum range. With these characteristics, CAPTAIN can study charged-current (CC) and neutral-current (NC) inclusive and exclusive channels in the important and poorly understood neutrino energy range where baryon resonances dominate. Like MINERvA, CAPTAIN can measure single charged and neutral pion production and single photon production. Measurements near the strange production threshold can also be made. The muon charge identification that comes from the MINOS near detector located behind MINERvA means that pure samples of both neutrinos and antineutrinos can be studied,

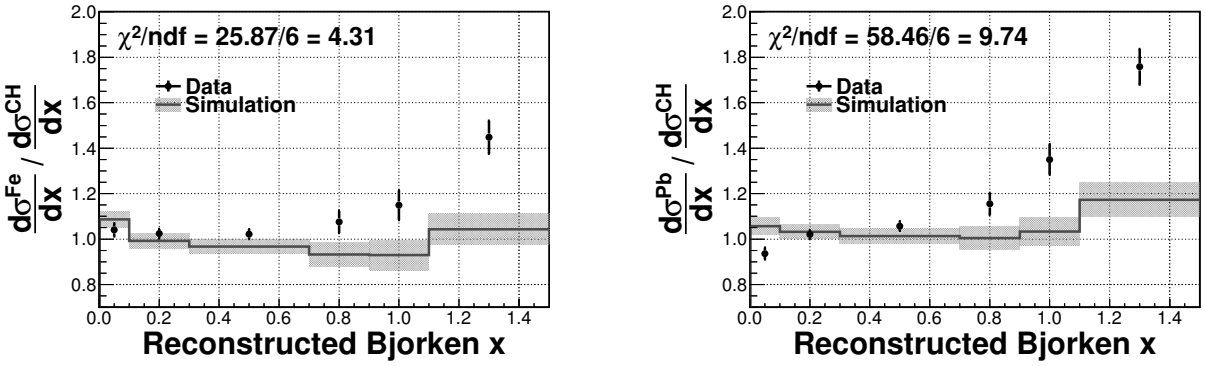

FIG. 2: Cross-section ratios between iron and hydrocarbon (left) and lead and hydrocarbon (right) as a function of the fractional momentum of the struck quark in the parton model ($x_{Bjorken}$).

which will be crucial for measurements of CP violation in the neutrino sector.

Simulations of the CAPTAIN detector geometry alone in the on-axis NuMI flux predict a 25% containment efficiency, where containment is defined to include all particles except leptons and neutrons. An estimated 250k contained events would be recorded per 10^{20} protons on target (POT). Thus, in one year, the experiment could collect 1-1.5 M contained events on argon and a similar number on plastic scintillator, depending on the NuMI beam power achieved during the run. (At the full power of 700 kW, NuMI will deliver 6×10^{20} POT per year). CAPTAIN would collect a comparable number of events in 2 years of antineutrino running. Figure 3 shows the relative sizes and possible placement of the CAPTAIN and MINERvA detectors. Given the placement of the CAPTAIN detector, there is also the possibility that the MINERvA detector could serve as a downstream hadronic calorimeter for events that start in CAPTAIN, which would mean that a much higher fraction of events would be contained. The CAPTAIN cryostat and vacuum system together comprise 1.5cm of steel which corresponds to less than one radiation length and less than a tenth of an interaction length of passive material between the two detectors.

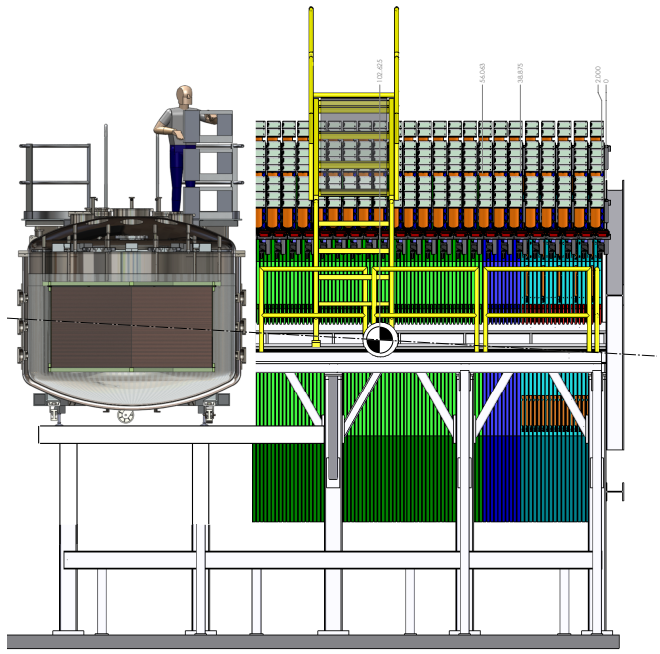

FIG. 3: Relative size and possible location of the CAPTAIN detector in front of the MINERvA detector. The neutrino beam travels from left to right at an angle of 58mrad to the horizontal.

The only other measurements on argon at these energies come from ArgoNEUT. The highest statistics sample comes from the inclusive cross-section measurement of 379 events integrated over the neutrino spectrum produced by the NuMI low energy beam[19]. With a fiducial mass approximately 20 times larger than the ArgoNEUT detector, CAPTAIN and MINERvA together will contain the hadronic system for a significant fraction of interactions that occur in argon. In addition, the proton exposure per year is expected to be 5 times the exposure of the ArgoNEUT run. There are measurements on argon planned at lower energies by the MicroBooNE experiment, which uses a 170-ton liquid argon TPC sitting in the Booster Neutrino Beamline (BNB). However, the neutrino energy in the BNB is less than 1.5 GeV, below the region of interest for long-baseline neutrino experiments that would address the neutrino mass hierarchy and CP violation. Measurements made by CAPTAIN in an on-axis position in the NuMI beam are therefore complementary to low-energy neutrino measurements made using MicroBooNE.

In addition to the physics program for CAPTAIN, running in neutrino and antineutrino beams with similar characteristics to the proposed next long-baseline neutrino beam will provide validation of the detector technology, including exclusive particle reconstruction and identification, shower reconstruction, and reconstruction of higher energy neutrino events with significant particle multiplicities. This last goal is unique to CAPTAIN; simulations indicate that 87% of all neutrino interactions in CAPTAIN will be resonant pion production or deep inelastic scattering, compared to MicroBooNE, in which 60% of the interactions are quasi-elastic.

In summary, both CAPTAIN and MINERvA share the goals of studying neutrino and antineutrino interactions that are important for future neutrino oscillation physics experiments, and measuring how the nuclear environment will modify those interactions. Combining the CAPTAIN and MINERvA detectors will provide precision measurements of nuclear effects and expand the physics reach of both experiments.

---

[1] J. J. Aubert *et al.* (European Muon Collaboration), Phys. Lett. **B123**, 275 (1983).
[2] J. J. Aubert *et al.* (European Muon Collaboration), Nucl. Phys. **B 293**, 740 (1987).
[3] M. Arneodo, Phys. Rep. bf 240, 301 (1994).
[4] D. F. Geesaman, K. Saito, and A. W. Thomas, Annu. Rev. Nucl. Part. Sci. **45**, 337 (1995).
[5] P. Norton, Rept. Prog. Phys. **66**, 1253 (2003).
[6] K. Rith, (2014), `arXiv:1402.5000`
[7] T. Akiri et al. (LBNE Collaboration), (2011), `arXiv:1110.6249 [hep-ex]`
[8] U. Mosel, O. Lalakulich, K. Gallmeister, Phys. Rev. Lett. **112**, 151802 (2014)
[9] G. A. Fiorentini *et al*, Phys. Rev. Lett. **111**, 022501 (2014).
[10] A. A. Aguilar-Arevalo *et al.*, Phys. Rev. **D81** 092005 (2010).
[11] R. Acciarri (Fermilab) *et al.*, Phys. Rev. **D90** 012008 (2014).
[12] L. Fields *et al*, Phys. Rev. Lett. **111**, 022502 (2014).
[13] B. Eberly *et al*, (2014) `arXiv:1406.6415` submitted to Phys. Rev. Lett.
[14] B.G. Tice *et al*, Phys. Rev. Lett. **112**, 231801 (2014).
[15] N. Formin *et al.*, Phys. Rev. Lett. **108** (2012).
[16] P. Khetarpal *et al.*, Phys. Rev. **C87**, 045205 (2013).
[17] A.Ankowski*et al*, `arXiv:1406.4080 [nucl-ex]`
[18] A. Higuera, A. Mislevic, *et al.*, (2014), `arXiv:1409.3835 [hep-ex]`, submitted to Phys. Rev. Lett.
[19] R. Acciarri (Fermilab) *et al.*, Phys. Rev. **D89** 112003 (2014).