Intent to initiate a JLAB program at the intersection of high precision neutrino physics and high precision electron physics

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Abstract

We intend to initiate a program of study at Jefferson Laboratory aimed at furthering our understanding of electron scattering off different nuclei in the quasi-elastic, resonance and inelastic regions using the Hall C and CLAS detectors. One important motivation for this work is to help us understand, in detail, neutrino-nucleon and antineutrino-nucleon cross sections and final states in the 0.5-3.0 GeV energy range. This information is critical for the success of planned next-generation accelerator-based neutrino oscillation experiments. Our first phase is the study of total cross sections and quasi-elastic scattering. This will become a broader program to understand and model the dominant hadronic final states produced in lepton-nucleon (electron and neutrino) interactions in the 0.5-3.0 GeV range. Our aim is to create data sets of events with final state hadrons such that neutrino experiments can apply the same set of cuts they use to the corresponding electron scattering data. For example, the selection of quasi-elastic events in neutrino scattering on nuclear targets requires the identification of the final state protons using specific cuts.

Contents

1 INTRODUCTION

A set of complementary investigations is being initiated in the electron-scattering and neutrino-scattering communities. The primary aim of this work is to improve our knowledge and modelling of electron and neutrino-nucleus(nucleon) scattering in the 0.5-3.0 GeV energy range. This is critical for the successful execution of the next generation of accelerator-based neutrino oscillation experiments planned in the US and Japan. Along the way a number of other physics topics necessarily will be explored, among them are quark-hadron duality, measurement of weak and electromagnetic form factors for bound nuclei, nuclear transparency and the determination of differential cross sections for the production of certain exclusive multi-particle final states in electron scattering and neutrino scattering.

The University of Rochester is leading an international collaboration involving both nuclear physicists and particle physicists, as well as physicists from the electron scattering and neutrino scattering communities, who are interested in both electroweak physics and QCD in nucleons and nuclei. The motivation of the electroweak community is to understand neutrino oscillations and neutrino flavor mixing. The goals of the QCD/nuclear physics community are to understand the properties of quark distributions in nucleons and nuclei, quark-hadron duality, QCD and current algebra sum rules and the structure of nucleons bound in nuclei.

As described above, future precision neutrino experiments will be performed with neutrino beams in the 0.5-3.0 GeV energy range. A deeper understanding of the QCD/nuclear effects is essential in the extraction of the mixing angles and neutrino masses. Therefore, the two communities have initiated a series of annual conferences called the Neutrino-Nucleus Interactions in the Few GeV Region (NUINT). NUINT 2001 was held at KEK in Japan [1]. NUINT 2002 was held at the University of Irvine [2]. The third conference in the series is scheduled to be held in Europe at the end of this year.

The current situation in neutrino physics demands further exploration of the inelastic, resonance and quasi-elastic regimes. The high energy and nuclear physics group at Rochester is attempting to tackle this problem coherently from a number of different angles. We plan to use data from completed experiments SLAC E140 [3] and JLAB E94-110 [4] and E99-118 [5], as well as from two approved Hall C experiments E02-109 [6] (spokepersons-Christy and Keppel) and E00-101/E03-103 [7] (spokesperson-Arrington) to explore the total form factors relevant for this work [8][9]. In addition, we are leading the push for a new Hall C experiment to run next summer, E03-110 [10] (with spokespersons Bodek and Keppel), which was recently proposed and received favorably by the PAC. In parallel, Manly, along with members of the CLAS collaboration, plan to study the relevant final states using the CLAS detector in Hall B. This work will begin with the study of quasi-elastic scattering and then expand to cover relevant mult-hadron states. Simultaneously, Rochester

(McFarland), along with Hampton (Keppel) and Fermilab (Morfin), are leading the effort to build a fully-active neutrino detector in the NuMI beam at Fermilab in order to study the corresponding physics in neutrino scattering [11] with high statistics. Rochester is also involved in a similar effort at JParc in Japan [12]. Finally, Bodek is leading a group of experimentalists and phenomenological theorists who will incorporate and merge all this information into a set of models that can be used by all interested parties (see, for example, references [8] and [9]).

2 Status of neutrino physics

Experimental evidence for oscillations among the three neutrino generations has been recently reported [13]. The most convincing measurements of neutrino oscillation come from the up-down asymmetry of the atmospheric neutrino flux measured by the Super-Kamiokande experiment. The size of this asymmetry points to a nearly maximal neutrino mixing, and corroborating data indicates a mass splitting, $\delta m^2{}_{\rm atm} \approx 3 \times 10^{-3}{\rm eV}^2$, with most of the ν_μ disappearing into ν_τ[13]. Solar neutrinos provide a second measurement of neutrino oscillations, and recent evidence from the SNO experiment[14] suggests that the solar neutrino transition is primarily from ν_e into other active neutrinos. It also suggests that the solution to the solar neutrino deficit is a large mixing MSW solution with a $\delta m^2 \sim 5 \times 10^{-5}{\rm eV}^2$. The very recent day/night asymmetry measurement from SNO offers direct evidence that this solution is correct. Recent results from KAMLAND support this conclusion [15]. The final and most controversial piece of evidence is the unconfirmed signature of $\overline{\nu}_e$ appearance by the LSND experiment [16]. If LSND has also observed neutrino oscillations, then a fourth and therefore "sterile" neutrino must be involved, a possibility disfavored by the solar and atmospheric data.

Assuming above atmospheric and solar neutrino observations are correct and that the LSND signature is not confirmed by the upcoming BooNE experiment at Fermilab, then the MNS neutrino mixing matrix, parameterized as

$$U_{MNS} \approx \begin{pmatrix} C_{12}C_{13} & S_{12}C_{13} & S_{13}e^{-i\delta} \\ -S_{12}C_{23} - C_{12}S_{23}S_{13}e^{i\delta} & C_{12}C_{23} - S_{12}S_{23}S_{13}e^{i\delta} & S_{23}C_{13} \\ S_{12}S_{23} - C_{12}C_{23}S_{13}e^{i\delta} & -C_{12}S_{23} - S_{12}C_{23}S_{13}e^{i\delta} & C_{23}C_{13} \end{pmatrix}$$

has two large mixing angles, θ_{12} and θ_{23}, and one, θ_{13} that is small, to accommodate the absence of $\overline{\nu}_e$ disappearance in the CHOOZ and Palo Verde experiments[17, 18]. The mass splittings are also highly non-degenerate in this scenario, one with $\delta m^2 \sim 5 \times 10^{-5}{\rm eV}^2$ and two with $\delta m^2 \approx 3\times \sim 10^{-3}{\rm eV}^2$. If $E_\nu/L \gg 10^{-4}$ ${\rm eV}^2$, then the probability in vacuum for a flavor transitions suppressed by this small angle, e.g., $\nu_\mu \to \nu_e$, can be approximated as

$$P(\nu_\mu \to \nu_e) \approx \sin^2 2\theta_{13} \sin^2 \theta_{23} \sin^2 \left(\frac{\delta m^2{}_{\rm atm} L}{4E} \right).$$

The effective two-generation mixing angle, $\theta_{\mu e}$ is defined so that

$$\sin^2 2\theta_{\mu e} \equiv \sin^2 2\theta_{13} \sin^2 \theta_{23}.$$

The atmospheric neutrino data favors a nearly maximal $\sin^2 2\theta_{23}$, so $\sin^2 \theta_{23} \approx 1/2$. A measurement of this transition probability therefore measures the small angle, $\sin \theta_{13} = |U_{e3}|$. The measurement of this sub-leading oscillation is analogous to searching for first and third generation mixing in the quark sector, which has led to a rich phenomenology of CP-violation, meson mixing and rare decays in the quark sector.

2.1 The Measurement of $\nu_\mu \to \nu_e$

If U_{e3} is in fact non-zero, then two important future measurements are possible. First, it is possible to determine directly the hierarchy of the neutrino masses by comparing $P(\nu_\mu \to \nu_e)$ to $P(\overline{\nu}_e \to \overline{\nu}_\mu)$ in matter[19]. This is not possible with vacuum oscillation measurements, because they probe only the magnitude of δm^2 and not the sign. However, the well-known matter enhancement of neutrino oscillations leads to a dependence in the transition probabilities on both the magnitude and sign of δm^2, thus allowing us to determine whether one small splitting implies two heavy and one light neutrinos or vice-versa.

Perhaps the most exciting possibility on the horizon is that it may turn out to be feasible to search for CP violation in the MNS matrix. CP violation occurs when there are two amplitudes contributing to a given process with a relative phase, and therefore CP violation in neutrino oscillations requires that the θ_{13} and δ parameters in the MNS matrix are non-zero. Practically, observation at the L/E appropriate for $\delta m^2{}_{\rm atm}$ also requires a large $\delta m^2{}_{\rm solar}$, such as in the large mixing-angle MSW solution so that the second contributing amplitude is not too small. This will be a challenging measurement and may ultimately require multi-megawatt beams and megaton size neutrino detectors, but the payoff in the end is potentially the observation of a profound connection between mixing in the quark and lepton sectors.

The first step on this roadmap is the observation of $U_{e3} \neq 0$ in the atmospheric δm^2 region. Conventional neutrino production, decay of mesons produced in proton fixed-target interactions, produces beams that are primarily muon neutrinos or anti-neutrinos. Therefore the discovery channel for U_{e3} is $\nu_\mu \to \nu_e$ and its charge conjugate. The desirable experimental characteristics in order to make a substantial improvement in U_{e3} past the CHOOZ bound are:

- $L/E \approx 4/\delta m^2{}_{\rm atm} \sim 400$ km/GeV

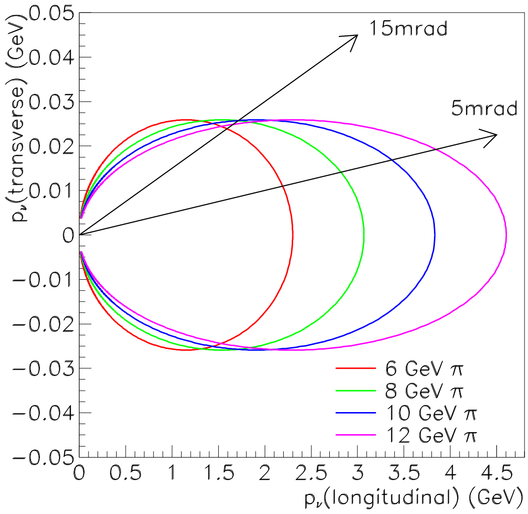

Figure 1: Schematic illustration of the off-axis beam technique. As can be seen, at a modest angle away from the focal axis of the pion beam (in this case, approximately 1° or 15 mr) pions of many different momenta all decay to neutrinos with approximately 1.5 GeV in an off-axis far detector.

- Low E_ν or highly active detector to reduce background from ν_μ neutral current interactions
- $> 10^3$ ν_μ charged current events in long-baseline detector (without oscillations)

The long-baseline experiments currently under construction, NUMI/MINOS and CNGS, can achieve the last of these criteria, but only at the cost of going to relatively high energy, which spoils the first two factors. Consequently, NUMI/MINOS and CNGS have very limited U_{e3} reach beyond the CHOOZ limit.

2.2 Off-axis Long Baseline Neutrino Experiments

Off-axis beams for neutrino oscillation experiments are highly desirable because they are nearly monochromatic. The reason for the narrow energy spectrum of such beams is illustrated schematically in Figure 1, which shows that charged pions of all energies decay to neutrinos of approximately equal energies at a fixed angle. This idea for beam construction is applicable and desirable for both long-baseline and short-baseline ("near") neutrino detectors. The variation in the neutrino flux as a function of distance from the neutrino beam axis (at roughly the downstream distance of the MINOS near detector) can be seen in Figure 2.

Neutrino appearance and disappearance probabilities are functions of L/E only. Therefore, in long-baseline oscillation experiments, a narrow

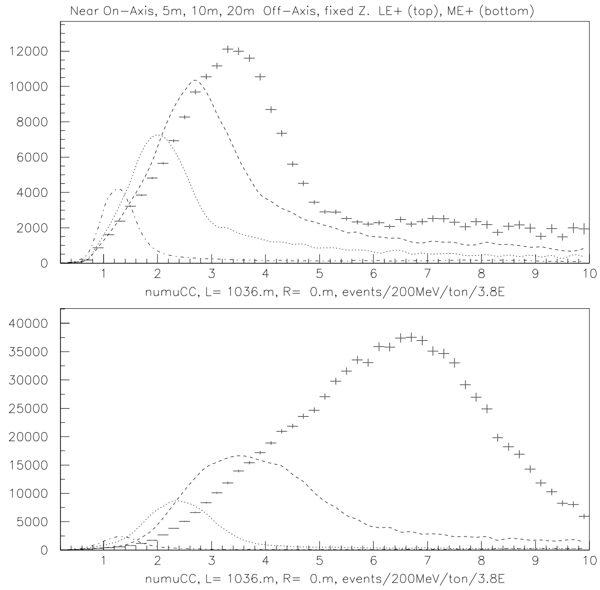

Figure 2: Relative event rate from the on and off-axis neutrino beams for the NuMI low energy (upper plot) and medium energy (lower plot) beams. The crosses correspond to the on-axis ν_μ neutrino-induced charge-current events, while the curves toward the left of the on-axis curve correspond to the event rates in detectors successively 5, 10, and 20 meters off axis, respectively.

band beam of the correct energy results in maximal oscillation probabilities. Another important feature for massive detectors with difficulty in separating neutral-current interactions of muon neutrinos from charged-current reactions of other flavors of neutrinos is the ability to use visible energy as a discriminant. For charged-current events, the total neutrino energy is observed in the detector, but for neutral-current events, the unobserved final state neutrino can carry off significant energy. Therefore, high energy neutral-current events appear as oscillation candidates at lower energy. A monochromatic beam minimizes this "feed-down" background from neutral-current interactions.

Currently, two $\nu_\mu \to \nu_e$ appearance experiments are being discussed using high-rate sources and off-axis neutrino beams. The first proposes to send an intense low energy neutrino beam from the 0.8 MWatt 50 GeV Proton Synchrotron (PS) currently being constructed at JAERI in Tokai, Japan to the existing Super-Kamiokande detector 295 km away[12], beginning as early as 2007. The beam for this experiment is a 2–3° off-axis beam with a peak energy of approximately 700 MeV. The second possible experiment, located at Fermilab, proposes to use the existing NUMI beam with a detector situated 0.6° off-axis at a distance of approximately 700 km[21]. This beam would have a peak energy of 2 GeV, thus making possible the observation of matter effects.

Both experiments have potential upgrade paths to more intense proton

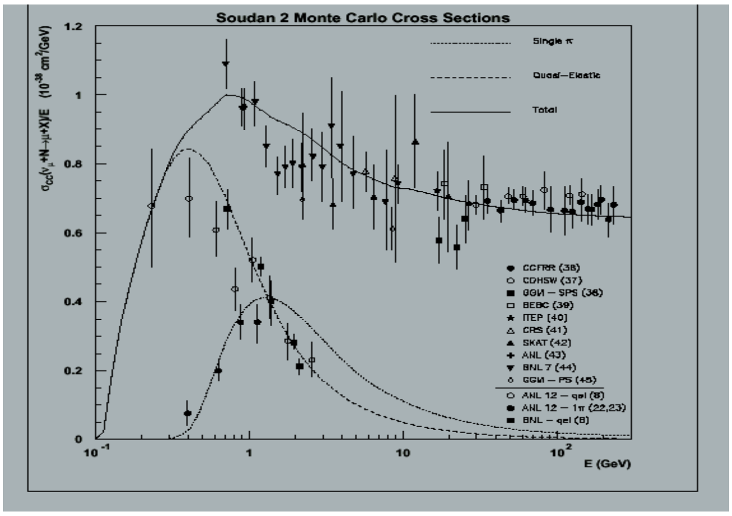

Figure 3: The total cross section for neutrinos as a function of energy with the single pion and quasi-elastic contributions shown.

sources and larger detectors should the initial running be successful in observing $|U_{e3}|$ and should other experiments make possible the future observation of leptonic CP violation.

2.3 Importance of low energy cross sections

As seen in Figure 3, for neutrino experiments below 1 GeV, the quasi-elastic cross section dominates. Most experiments in this region, e.g., water Cerenkov experiments, can only observe the final state muon and are not sensitive to recoil nucleons. The energy of the events is obtained under the assumption that the reaction was quasi-elastic. Therefore for experiments in the 1 GeV range, background predictions require knowledge of how often inelastic scattering events look like a quasi-elastic events. In the 2–3 GeV region, the inelastic cross section dominates with a significant contribution from quasi-elastic events. In this energy region, the unobserved hadrons are very important. Even detectors which are sensitive to hadronic final states, e.g., sampling calorimeters, have a different response to charged and neutral pions. The energy calibration and the misidentification of NC events as CC ν_e events is very dependent on the fraction and fragmentation function of neutral pions in the final state.

To see the importance of understanding the cross section for neutrino oscillations, one only needs to examine Figure 4, published by the K2K Collaboration earlier this year [20]. The dip in the event spectrum at an energy just below 1 GeV is the signal for neutrino oscillations via ν_μ disappearance. The position of the dip gives a measure of δm^2 while the depth of the dip gives a measure of the mixing angle (θ_{23} in this case). The next generation of

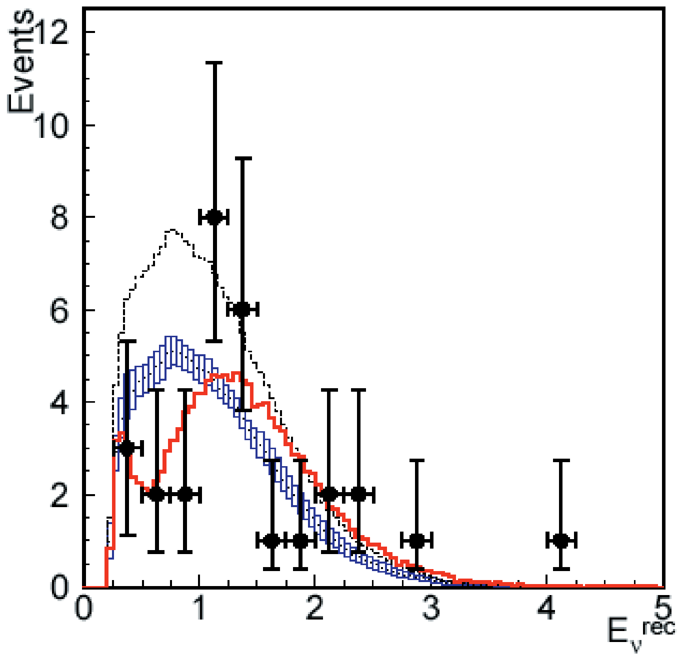

Figure 4: Results on oscillations from the K2K collaboration from reference [20]

neutrino experiments will have better statistics. However, they are planning to measure θ_{13} which is known to be a much smaller mixing angle. A very good understanding of the expected cross section, as well as the response of the detector to the different types of events in the quasi-elastic and resonance regime is needed in order to make this measurement.

At present, the neutrino differential cross sections for charged-current and neutral-current events, and the hadronic final states in the 2–3 GeV region are not well understood. The lack of good data in this region limits the physics capabilities of any future neutrino oscillations experiment. The measurements of interest are:

- Total and differential cross sections for charged-current and neutral-current interactions with nucleons
- Weak and electromagnetic form factors in bound nucleons
- Resonance excitation form factors in bound nucleons
- Hadronic final states in charged-current and neutral-current interactions with nucleons and nuclei
- Detailed understanding of nuclear binding effects, including Fermi motion, binding energy, interactions of final state hadrons in the nucleus

- Coherent nuclear processes

In each case, the current data in the 1–few GeV region has large uncertainties. For example, Figures 5 and 6, taken from reference [8], show the quasi-elastic cross section for ν and $\overline{\nu}$ along with curves from recent theoretical modelling by Budd, Bodek and Arrington.

Theoretical models exist that characterize the reactions of interest and relate νA scattering to well-measured eA processes. These models do not provide predictions for neutrino scattering cross-sections and final states, but rather lend theoretical guidance to interpreting precise low energy neutrino scattering data as it becomes available.

As mentioned earlier, a fully active near detector is being proposed for the NuMI beam at Fermilab in order to make precise measurements of νA and $\overline{\nu} A$ cross sections in the 0.7-3.0 GeV energy range [11]. One concept of the detector is shown in Figures 7 and 8. Complementary eA measurements will be necessary to fully utilize the information gathered in this experiment.

3 Electron scattering

The electron scattering and neutrino scattering communities are joining to collect eA data, and later νA data [11], in this energy regime. The motivation for the neutrino community, spelled out in some detail already, is to reduce uncertainties in the models of νA processes by relating them to well-measured eA processes and, in turn, reducing uncertainties in future neutrino oscillation measurements. The electron community will gain data useful for understanding quark-hadron duality in nuclear targets in both electron and neutrino scattering, form factors for bound nucleons and nuclear binding effects on the produced final states. In particular, by using similar cuts on appropriate electron and neutrino data sets, we will be able to extract an improved measurement of the weak form factor.

Two directions in electron scattering are being pursued. The first is an effort to understand nuclear effects on the form factors. This work will make use of existing data from SLAC E140 [3] and JLAB E94-110 [4] and E99-118 [5], as well as from two approved Hall C experiments E02-109 [6] (spokepersons-Christy and Keppel) and E00-101/E03-103 [7] (spokesperson-Arrington). In addition, we are leading a proposal to measure the longitudinal-transverse separated structure functions from nuclear targets in the resonance region. This has been proposed (and favorably received by the PAC) for Hall C as E03-110 [10], which will build on the approved experiment E02-109.

The second effort will make detailed measurements in order to understand and better model the dominant hadronic final states produced in this energy regime. This work will be pursued using the CEBAF Large Acceptance Spectrometer (CLAS) detector facility in Hall B [33] at JLAB, shown in schematic form in Figures 9 and 10. The CLAS detector is ideal for studying quasi-elastic and inelastic eA scattering in the energy range of interest.

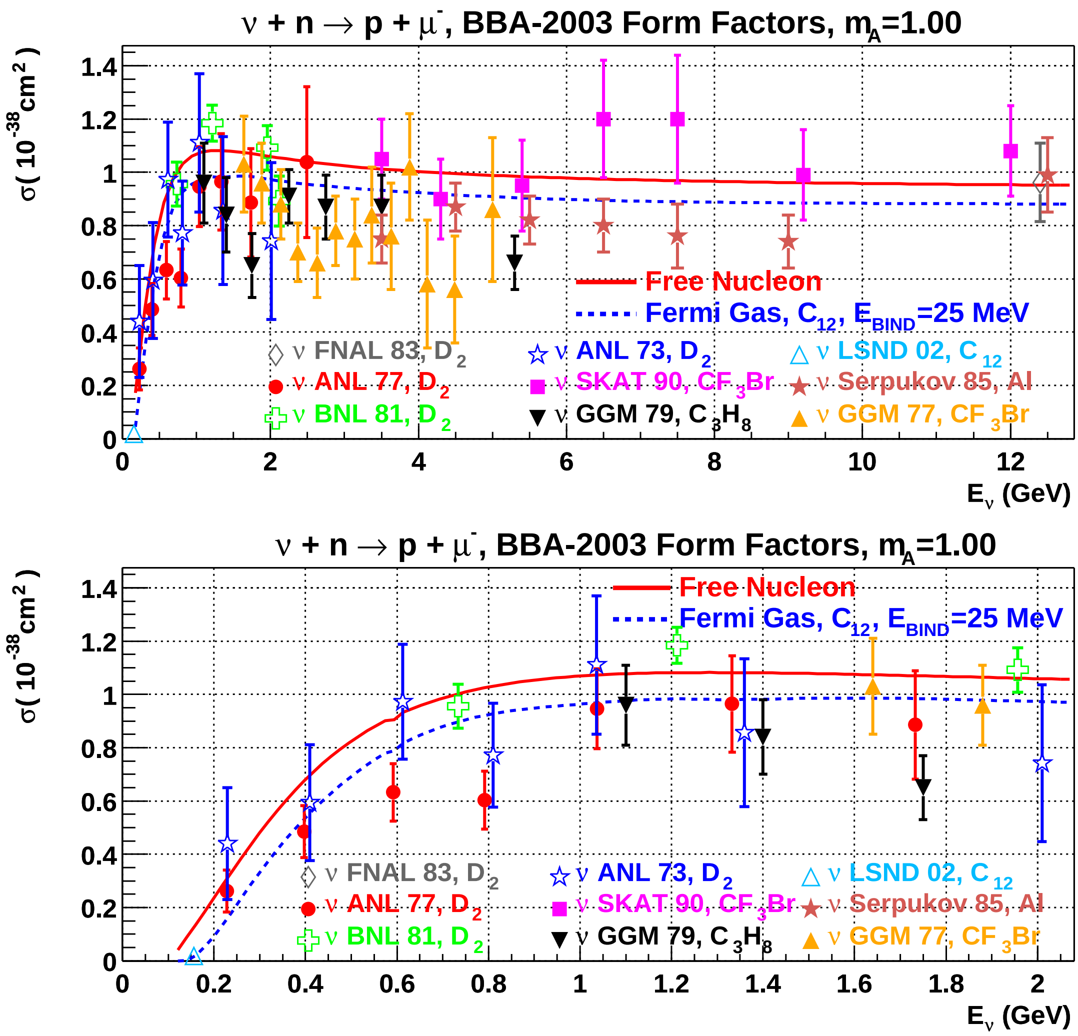

Figure 5: The QE neutrino cross section along with data from various experiments. The solid curve uses no nuclear correction, while the dotted curve [22] uses a Fermi gas model for carbon with a 25 MeV binding energy and 220 Fermi momentum. The lower plot is identical to the upper plot with the E_ν axis limit changed to 2 GeV. The data shown are from FNAL 1983 [23], ANL 1977 [24], BNL 1981 [25], ANL 1973 [26], SKAT 1990 [27], GGM 1979 [28], LSND 2002 [29], Serpukov 1985 [30], and GGM 1977 [31].

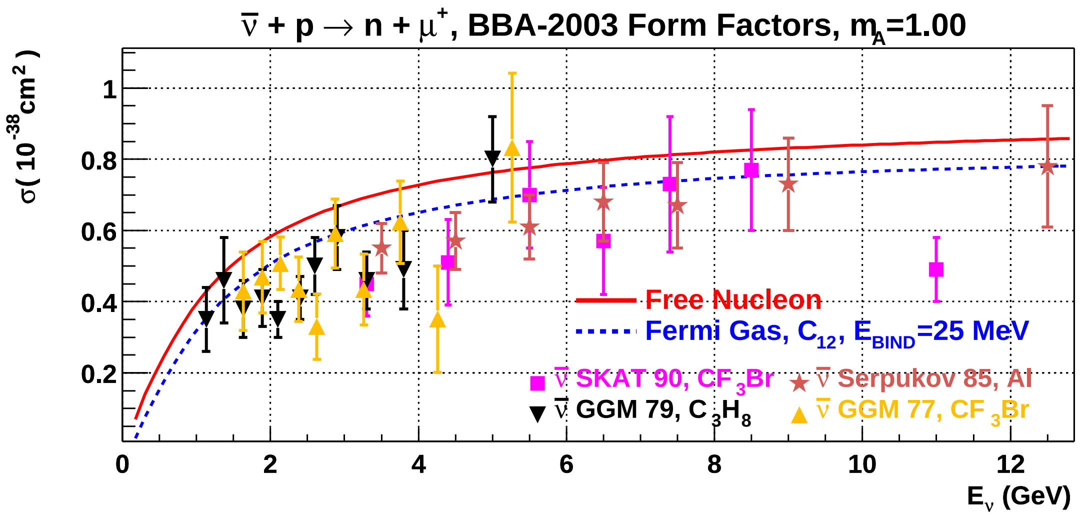

Figure 6: The QE antineutrino cross section along with data from various experiments. The solid curve uses no nuclear correction, while the dotted curve [22] uses a Fermi gas model for carbon with a 25 MeV binding energy and 220 MeV Fermi momentum. The data shown are from SKAT 1990 [27], GGM 1979 [32], Serpukov 1985 [30], and GGM 1977 [31].

This facility provides efficient detection of charged and neutral hadrons over a substantial fraction of the full solid angle. The high data rate means there should be sufficient data for differential measurements of quantities of interest. In addition, the detector is commissioned and has a well-developed software infrastructure to support analyses. Finally, having run since 1997, CLAS has collected a substantial amount of data relevant for this work already.

An example of how poorly understood is the hadronic final state production in νA interactions can be seen in Figure 11 for single pion production. Even in this simple case, experimental measurements vary by a factor of two in the 0.5-3.0 GeV energy range.

The work will begin by examining quasi-elastic scattering, as it is the dominant process at the lower end of the energy range of interest to the neutrino oscillation experiments and constitutes a significant fraction of the higher energy events. ν_μ charged-current or neutral-current inelastic events with an electron in the final state and missing particles constitute one of the two major backgrounds in the oscillation experiments. (The other is the small percentage of ν_e in the initial beam.) Clearly, a detailed understanding and accurate model of the quasi-elastic process in this energy range and knowledge of how things change with various experimental cuts is needed.

As can be seen in Figures 5 and 6, the QE cross sections are poorly understood for ν and $\bar{\nu}$ in this energy regime. The curves come from recent work by Budd, Bodek and Arrington, who have re-analyzed past data with updated form factors to calculate the total and differential QE cross sections [8]. According to these authors, the solid curve uses no nuclear cor-

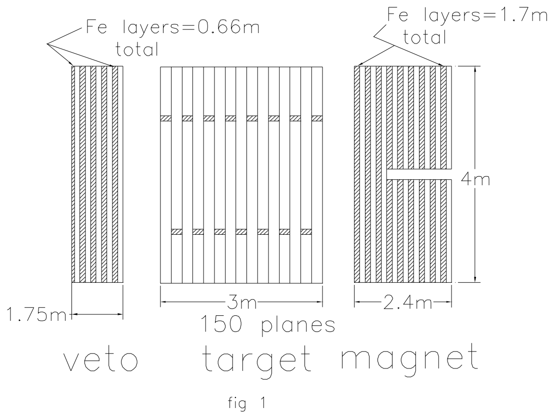

Figure 7: One concept of the near-source neutrino experiment planned for the NuMI beam at Fermilab, showing a 4 m x 4 m x 3 m active scintillator target, followed by a sampling calorimeter and magnetized range detector and preceded by an instrumented upstream veto.

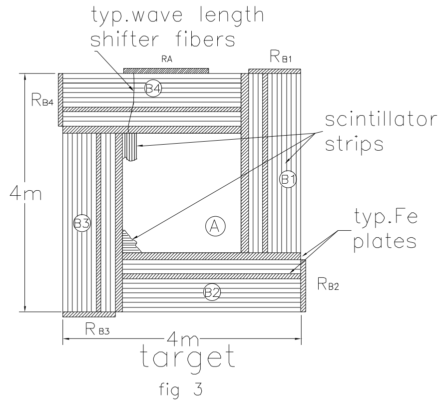

Figure 8: Concept of one plane of the active target in the near-source neutrino experiment.

rection, while the dotted curve [22] uses a NUANCE [34] calculation of a Smith and Moniz [35] based Fermi gas model for carbon. This nuclear model includes Pauli blocking and Fermi motion, but not final state interactions. As one can see from the data, the Fermi gas nuclear correction may not be sufficient. Tsushima *et al.* [36] studied the effect of nuclear binding on the nucleon form factors. They stated that modifications in bound nucleon form factors reduce the cross section relative to free nucleon form factors by 8%. Budd, Bodek and Arrington plan to study the nuclear corrections, adopting models which have been used in precision electron scattering measurements from nuclei at SLAC and JLab. They conclude that a complete understanding of quasi-elastic scattering requires an accurate measurement of both the normalized cross section versus energy as well as the shape of the Q^2 distribution. In addition, nuclear effects such as Pauli blocking and modification of nucleon form factors in bound nuclei need to be included.

One of our goals is to support this work by examining existing eA quasi-elastic scattering results and using CLAS data (existing already where possible, propose to take where needed) to refine our experimental knowledge and provide the best experimental input to the modelers. We plan to create a data set on which the neutrino experiments/modelers can see the effect of various cuts on a corresponding sample of eA data.

Later, the program of study will expand to cover resonance final states, where the neutrino detector response can vary dramatically. Again, it will be important to understand cross sections, angular distributions and nuclear

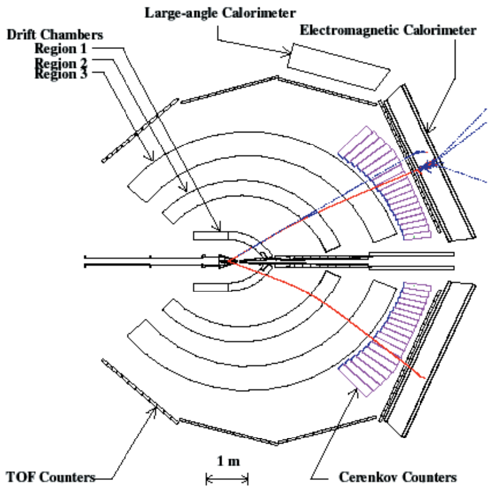

Figure 9: Side view of the CLAS detector, extracted from reference [33].

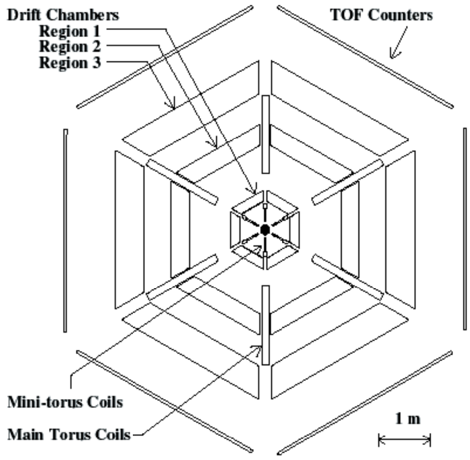

Figure 10: Beam view of the CLAS detector, extracted from reference [33].

effects.

4 Conclusion

It is our intent to initiate a program of study that lies at the intersection of high precision neutrino and high precision electron scattering physics. We will construct a comprehensive eA data set that can be used for comparison to neutrino data. We will measure the weak and electromagnetic form factors, study quark-hadron duality and measure the differential cross sections for exclusive final states in electron and neutrino scattering in the 0.5-3.0 GeV energy range.

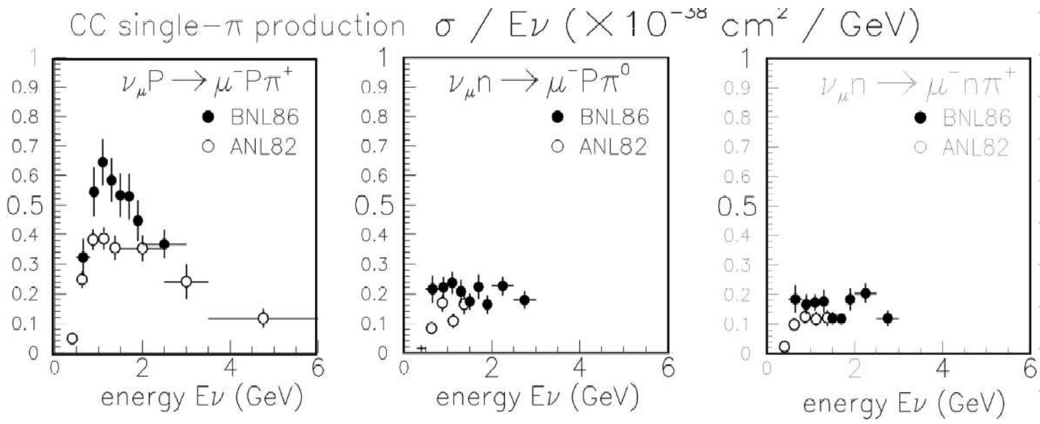

Figure 11: Neutrino charged current single pion production cross section data. Even in this simplest channel, the errors are large and the data are not consistent. Note that good measurements of both the total cross sections and kinematic distributions of all the final states are needed.

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