Neutrino Physics with a Near Detector on the Fermilab Booster Neutrino Beamline

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The Booster neutrino beamline at Fermilab provides the world's highest intensity neutrino beam in the 0.5-1.0 GeV energy range. There is a wealth of neutrino physics that can be accomplished using this beam. FINeSE (Fermilab Intense Neutrino Scattering Experiment) would consist of a 10-ton detector located 100 meters from the Booster neutrino source. This experiment would definitively measure the strange quark contribution to the nucleon spin. In addition, it could investigate neutrino-nucleon charged-current quasielastic, neutral-current elastic, charged- and neutral-current pion-production reactions, and neutrino-electron elastic scattering. This detector would also complement the existing MiniBooNE program by measuring these cross sections and providing a better understanding of the Booster neutrino source.

1. Introduction

The recently commissioned MiniBooNE experiment [1] is currently conducting a search for $\nu_\mu \rightarrow \nu_e$ oscillations at Fermilab. The neutrino source for MiniBooNE will provide the world's highest flux of muon neutrinos in the 0.5 – 1.0 GeV energy region. This source can be used to investigate several (non-oscillation) physics topics of interest in nuclear and particle physics. An oscillation distance is not needed for these physics topics, so the detector may be located close to the source. This will maximize the flux, allow for a relatively modest-sized detector, and still provide large event samples. A 10-ton active-target segmented detector would observe approximately 500k events in a two year run period. This event sample would be the largest ever collected in this energy region allowing for precision measurements.

With this neutrino beam, the dominant scattering processes are muon-neutrino charged-current (CC) quasielastic, neutral-current (NC) elastic, and muon-neutrino CC and NC scattering with pion production.

A compelling physics topic accessible via these scattering processes is an investigation of the strange quark contribution to the nucleon spin. Nucleon spin structure has been the subject of intense effort in the nuclear physics community over the past two decades with no definitive result. A measurement of neutrino-nucleon elastic scattering can provide a complementary and definitive test. In addition to strange spin physics, the measurement of total and differential cross sections for these neutrino scattering processes is of much theoretical and practical interest. Data on these reactions in this neutrino energy range is scarce. Finally, a measurement of these processes would greatly enhance the MiniBooNE neutrino oscillation program.

FINeSE (Fermilab Intense Neutrino Scattering Experiment) is currently under design to investigate these topics.

2. Physics Capabilities

The measurements described below are of interest in both particle and nuclear physics, and to neutrino experiments operating in this energy region.

2.1. Strange Quark Contribution to Nucleon Spin

The role played by strange quarks in the properties of the nucleon is not well understood. Deep inelastic scattering (DIS) of neutrinos on nucleons indicates that a substantial fraction of the nucleon momentum is carried by strange quarks [2]. However, the latest results from parity-violating electron scattering at MIT/BATES and Jefferson Lab show that the contribution from strange quarks to the magnetic moment of the nucleon is consistent with zero [3,4] (albeit with large uncertainties).

Results from DIS of polarized leptons on nucleons have been interpreted, via their measurements of the polarized structure function, g_1^p, as evidence that the strange quark contribution to the spin of the proton, Δs, is non-zero and *negative* [5]. The methods of extracting Δs from g_1^p are subject to some criticism due to assumptions regarding $SU(3)$ symmetry [6] and extrapolations to $x \to 0$. Recent results from HERMES [7] semi-inclusive DIS have further clouded the situation as these show indications for a small *positive* value for Δs.

Measuring NC neutrino-nucleon elastic scattering offers the opportunity to clarify this situation, because this process is uniquely sensitive to the spin of strange quarks in the nucleon. Also, extracting Δs from this process does not rely on the same assumptions as are needed for the DIS data. A measurement with sufficiently small systematic and statistical errors would allow for a definitive conclusion to the question of the strange quark contribution to the nucleon spin. The goal of this experiment is to perform this measurement with sufficiently small statistical and systematic errors so as extract the value for Δs to better than ± 0.03, the value quoted by recent DIS measurements [5].

This measurement of strange quark contributions to the nucleon spin using neutrino scattering is complementary to the large parity violating (PV) scattering programs at MIT/BATES, Jefferson Laboratory, SLAC, and Mainz. It is important to remember that PV electron scattering is most sensitive to the vector form factors and less sensitive to the axial form factor (and, therefore, to Δs). In fact, an extraction of Δs from PV electron scattering measurements is not likely possible [3]. This is in contrast to the neutral-current neutrino scattering process which is much more sensitive to the axial form-factor [8] and, therefore, an excellent process in which to look for strange-quark contributions to the nucleon spin.

A measurement of neutrino-proton (νp) and antineutrino-proton ($\bar{\nu} p$) elastic scattering was made by Experiment E734 at Brookhaven National Laboratory (BNL) using a 170 ton tracking detector in the BNL wide-band neutrino beam ($\bar{E_\nu} = 1.3$ GeV) [9]. From a sample of 951 νp and 776 $\bar{\nu} p$ elastic scattering events, they extracted differential cross sections ($d\sigma/dQ^2$) for $0.4 < Q^2 < 1.1\,(\mathrm{GeV/c})^2$. Based on this data, the calculated neutrino and antineutrino cross sections, and known values for the proton form factors, they extracted a non-zero value for the isoscalar contribution to the proton axial form factor [9].

The non-zero value for Δs as obtained by BNL E734 was later reexamined [10]. This reanalysis more carefully considered the effects of strange contributions to the vector form factors and the Q^2 evolution of the axial form factor in the differential cross sections for νp and $\bar{\nu} p$ elastic scattering. The results from this work showed that the BNL results are consistent with a value for Δs from -0.21 to 0 depending on the value used for the axial-vector mass, M_A. So, no definitive statement for the value of Δs could be made.

2.1.1. Experimental Method for Extracting Δs

The interactions of neutrinos and quarks are well-understood in the standard electroweak model. Our ignorance of details of the quark content of the nucleon can be parameterized into a few form factors. This allows for the differential cross section, $d\sigma/dQ^2$, for neutral- and charged-current scattering of neutrinos and antineutrinos from nucleons to be written as a function of the nucleon form factors: F_1, F_2 (vector) and G_1 (axial-vector) [11]. These form factors may be decomposed into contributions from the light quark currents. The CC form factors only contain contributions from isovector quark currents (involving only up and down quarks). However, the NC form factors are sensitive to any isoscalar contributions such as that from strange quarks.

Using the conserved-vector-current (CVC) hypothesis and the standard electroweak model [11], it is possible to relate these form factors to those known from electron scattering and beta decay, up to the strange quark contribution present in the NC form factors. Therefore, by measuring NC neutrino-nucleon cross section, and employing these known form factors, one may extract the strange quark contribution to the nucleon.

The differential cross section for neutrino-nucleon neutral-current scattering is quite sensitive to the axial-vector neutral current form factor G_1. As mentioned above, this may be written in terms of known form factors plus an unknown strange quark contribution [10],

$$G_1 = \left(-\frac{G_A}{2}\tau_z + \frac{G_s}{2}\right), \tag{1}$$

where $\tau_z = +1(-1)$ for scattering from protons (neutrons). This strange axial form factor, G_s, is identified with the strange quark contribution to the nucleon spin, Δs, in the limit of zero momentum transfer ($Q^2 = 0$).

The Booster neutrino beam line would provide an ideal source of neutrinos for this measurement because of the high flux and energy spectrum. The large neutrino flux provides high CC and NC scattering event rates and the neutrino energy is in a range where the momentum transfers are large enough to minimize nuclear model corrections yet small enough so that the form factor evolution with Q^2 is less of a concern.

By measuring appropriate ratios of CC and NC neutrino cross sections from protons and neutrons, one may maximize sensitivity to Δs while minimizing the experimental effects such as systematic uncertainties in the neutrino flux or the response of the detector to hadrons. It is also possible to minimize systematic errors due to the uncertainties in the form factors, such as the Q^2 evolution or the unknown strange quark contributions to the vector form factor F_2. In addition, a measurement of these ratios as a function of Q^2 with both neutrino and antineutrino running, would allow for a measurement of both Δs and F_2 and an understanding of the Q^2 evolution of the form factors [12–14].

The most sensitive cross section ratio to the effects of strange quarks in the nucleon is [15]

$$R(p/n) = \frac{\sigma(\nu p \to \nu p)}{\sigma(\nu n \to \nu n)}. \tag{2}$$

A measurement of $R(p/n)$ with a systematic error of 10%, would allow the extraction of Δs with an error of 0.03. This error is on the order of the error quoted by the latest results on Δs extracted from DIS [5]. However, this systematic error is difficult to achieve given the experimental difficulties of neutron detection. A less sensitive, yet experimentally more accessible, cross section ratio is

$$R(NC/CC) = \frac{\sigma(\nu p \to \nu p)}{\sigma(\nu n \to \mu^- p)}. \tag{3}$$

A measurement of $R(NC/CC)$ with a systematic error of 5% would yield Δs with an error of approximately 0.03, comparable to the DIS results.

These ratios may be measured with high statistical precision with a a 10 ton detector at a 100 meter location on the Booster beam line in 2 years of running. The event distributions for neutral- and charged-current neutrino scattering events are shown in Figure 1 as a function of squared momentum transfer, Q^2. Approximately 400k CC events and 50k NC events will be observed (assuming 100% efficiency) in the Q^2 range indicated. The ratios are shown in Figure 2 as a function of squared momentum transfer, Q^2, for a range of Δs values. As can be seen from this figure, the statistical errors are quite small due to the high event rates. The sensitivity to Δs in these ratios is indicated by the separation of the three lines in each plot and sets the allowed systematic error to achieve the goal of measuring Δs to ±0.03.

2.2. Cross Section Measurements

High-precision measurements of CC and NC cross sections in the intermediate energy range of the Booster neutrino beam would be of great theoretical and practical value. In this energy range, quasi-elastic CC scattering is the dominant process. However, other processes including NC elastic scattering as well as CC and NC production of pions are accessible. A measurement of the absolute and differential cross sections for all of these

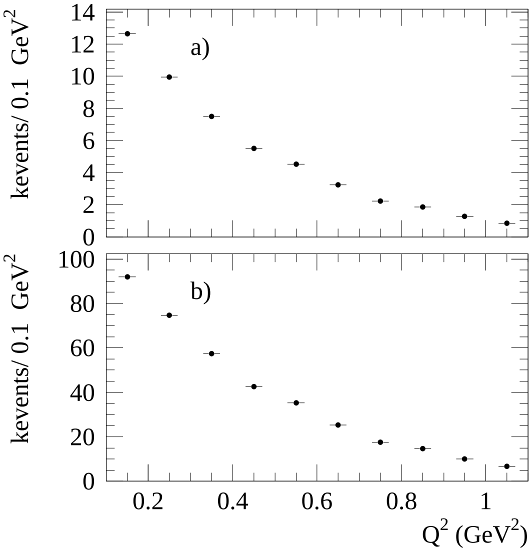

Figure 1. Event distributions for (a) $\nu_\mu - N$ neutral-current scattering and for (b) $\nu_\mu - N$ charged-current scattering with $\Delta s = 0$. These distributions are calculated for a 10-ton detector at a 100 meter location on the Fermilab booster neutrino beamline in two calendar year of data-taking.

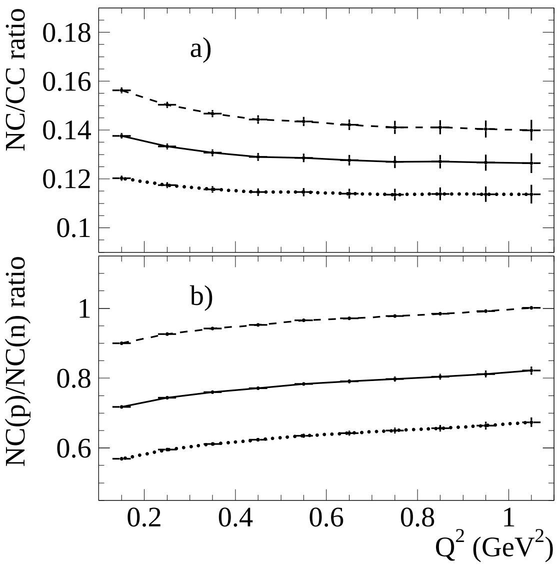

Figure 2. Cross section ratios for (a) $\nu_\mu - N$ NC/CC scattering and for (b) $\nu_\mu - p/\nu_\mu - n$ NC ratio for $\Delta s = 0.0$ (solid), $\Delta s = -0.1$ (dashed), and $\Delta s = +0.1$ (dotted). These statistical errors are calculated assuming two calendar year of data-taking.

reactions in this energy region, where the existing data is sparse, would be of much interest.

The interactions of neutrinos with quarks, the constituents of nucleons, is theoretically well-understood and devoid of radiative corrections. Therefore, the neutrino interactions with nucleons should yield further insight into nucleon structure and would complement the large effort in this direction at Jefferson Lab [16].

From a practical standpoint, a quantitative understanding of these reactions is important for many experiments that search for neutrino oscillations in this energy region. Cross section measurements would provide valuable input for atmospheric neutrino oscillation searches as well as the MiniBooNE and K2K accelerator-based neutrino searches.

Neutrino-electron elastic scattering can provide information on Standard Model and beyond-the-Standard Model physics. For example, a non-zero neutrino magnetic moment will give rise to an electromagnetic contribution to NC neutrino scattering, most easily measured using neutrino-electron elastic scattering. For a given neutrino energy, the electromagnetic contribution to the neutrino-electron cross section increases rapidly with decreasing electron recoil energy, while the Standard Model contribution increases only gradually. The resulting shape dependence in the differential cross section can be used to look for a signal in a high-statistics experiment without error contributions due to uncertainty in neutrino flux. Sensitivity to neutrino magnetic moment therefore depends upon electron recoil energy measurement and the number of scatters measured. Unfortunately, the event rates for neutrino-electron scattering in a 10-ton detector are quite low (approximately 100 events in 2 years running) and would not allow for a significant improvement in sensitivity to a neutrino magnetic moment. However, it can develop the technology necessary to identify very low energy electron recoils to make possible a significant improvement in this measurement with a larger detector and greater beam flux.

2.3. Neutrino Oscillations with MiniBooNE

At a location only 100 meters from the neutrino horn, this new detector will record comparable event rates to the full MiniBooNE detector. With this high-statistics event sample, this detector can be used as a "beam monitor" to measure the product of muon and electron neutrino flux and the cross section. The detector will have excellent energy resolution and particle identification capabilities which will allow precise measurements of the beam electron and muon neutrino rates as a function of energy. These measurements can then be combined with measurements in the MiniBooNE detector to do improved searches for ν_μ to ν_e appearance oscillations and for ν_μ disappearance oscillations. For example, this detector will directly measure, to an accuracy of 3-4%, the beam ν_e rate from muon and kaon decay; this should be compared to the systematic uncertainties in MiniBooNE, which are around 7-8%. For ν_μ disappearance measurements, the single detector MiniBooNE experiment will be limited to the uncertainties in the beam flux and cross section which probably cannot be reduced to much below 15%. With this detector the flux could be measured very accurately, leading to a much improved disappearance measurement at the few percent level. The timely completion of this experiment could be a very important component of the MiniBooNE program. If MiniBooNE sees an oscillation signal, this detector will help the measurement by reducing the beam ν_e uncertainties, provide much improved oscillation parameter determinations, and allow a precision probe of ν_μ disappearance in the Δm^2 region of the signal. If MiniBooNE does not see a signal, this detector will expand the region excluded for both appearance and disappearance oscillations.

3. Experiment

These measurements may be executed by constructing a 10-ton segmented detector approximately 100 meters from the neutrino source on the Booster beam line. A schematic view of the location of this near detector is shown in Figure 3.

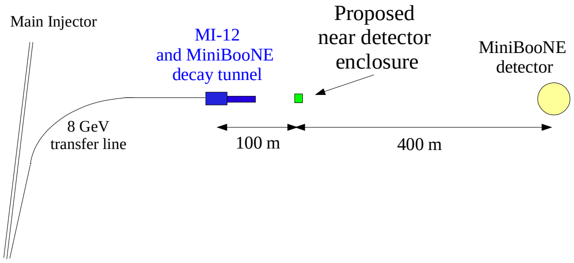

Figure 3. Proposed near detector location with respect to the existing Fermilab Booster neutrino target building (MI-12) and MiniBooNE detector.

3.1. The Booster Neutrino Beam

The Booster neutrino beam will provide an intense source of muon neutrinos with a small background of electron neutrinos in the energy range of 0. – 1.5 GeV with a mean energy of approximately 800 MeV. This energy spectrum is close to ideal for these measurements. The neutrino beam is of sufficient energy to provide large event rates in the momentum transfer region of interest, yet has only a small high-energy component which could lead to undesirably high backgrounds in the detector. It is also an energy region of interest for current oscillation experiments, both accelerator-based and atmospheric.

Using the currently estimated Fermilab Booster neutrino flux and assuming 2.5×10^{20} protons on target per year, there would be approximately 500k neutrino scattering events in a detector with 10 tons of active volume in one year. This would provide a unprecedented neutrino event sample in this energy range.

In addition, as has been demonstrated with the first beam-induced events from MiniBooNE, this beam has an excellent time-structure for doing neutrino physics. The 1.6μs width of the booster spill onto the neutrino target, provides a low duty-factor ($\approx 10^{-5}$) neutrino beam which virtually eliminates cosmic ray background in these measurements. Also, the maximum 15 Hz spill frequency provides ample inter-spill time for detector readout which decreases complexity and expense.

3.2. The Detector

To execute these measurements, the detector would have to meet several criteria. First, it would have to consist of an active target with a minimum of "dead" regions. It would need to be able to resolve particle directions and energies for muons, protons, charged and neutral pions, and (ideally) neutrons. These design characteristics are necessary to minimize the systematic errors that arise from particle misidentification and from unknown efficiencies. The statistical errors, with these event rates, will be quite small – the challenge is to minimize systematic errors.

Because of these requirements, an "open-volume" Čerenkov detector such as used by MiniBooNE would not be adequate. Final-state particles are not tracked individually; this results in unacceptably high particle misidentification for these measurements. A segmented detector which can track individual particles (shown schematically in Figure 4) will be required.

Figure 4 also indicates the NC/CC ratio method proposed to measure Δs. With a sufficiently segmented detector, the efficiency for detecting the scattered proton will be independent of the presence of a final-state muon. If this can be realized, the efficiency for proton detection will cancel in the ratio, reducing the systematic error requirement of 5% for the ratio to a systematic error on the muon efficiency of 5%, a quite reasonable goal.

The best method to meet these requirements may be segmented solid scintillator detector read out with optical fibers coupled to multichannel CCD arrays. Methods of extruding solid scintillator with embedded readout fibers have become common and are used in many detectors. The optimal size and orientation of the scintillator strips is currently under study. The CCD technology has become more advanced and has been successfully implemented in several experiments. This method provides many channels for fiber readout at a low price.

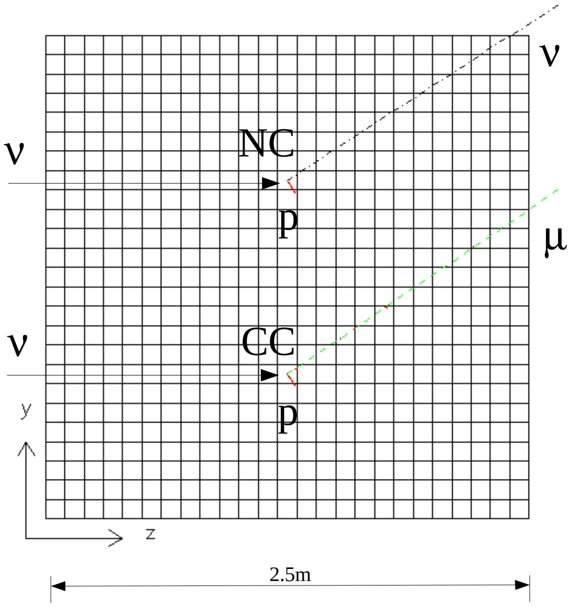

Figure 4. Schematic diagram of the near neutrino detector with neutral-current and charged-current neutrino scattering events as simulated by GEANT superimposed. For these events E_ν = 800 MeV and $Q^2 = 0.2$ GeV^2 which results in a proton kinetic energy of approximately 100 MeV and lepton kinetic energy of approximately 600 MeV. The proton range is approximately 10cm in scintillator.

It is currently estimated that a solid detector of 2.5 m on a side (approximately 15 tons) would provide a 10-ton fiducial volume. The goal of reconstructing NC elastic scattering events down to $Q^2 = 0.1$ GeV^2 implies that protons of 50 MeV should be reconstructible. This sets the scale for the scintillator segmentation to be on the order of a few centimeters.

4. Summary

FINeSE, a neutrino experiment built at a near location on the Booster neutrino beam line would make many important nuclear and particle physics measurements. The neutrino beam has been constructed and is currently delivering neutrinos to the MiniBooNE experiment. To execute this experiment, a building and detector would need to be constructed at a near location on the beam line. However, the construction of both of these items would be relatively straightforward, of reasonable cost, and would result in a great addition to the FNAL neutrino program.

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