A Fine-grained Detector to Study Nuclear Effects in a NuMI Neutrino Scattering Experiment

Jorge G. Morfín
Fermi National Accelerator Laboratory,
P.O. Box 500, Batavia, IL,
60510

Abstract. The NuMI Facility at Fermilab will provide an extremely intense beam of neutrinos making it the ideal location for high statistics (anti)neutrino-nucleon/nucleus experiments. With such intensities, a fine-grained, solid scintillator detector becomes practical. The ability of such a detector to examine so-far unstudied nuclear effects in neutrino scattering will be addressed. Recent theoretical work suggests that such effects will be considerably different than those measured with electron and muon beams.

1. Introduction

The upcoming neutrino oscillation experiments around the world are driving the construction of new, very-intense neutrino beamlines. These new beamlines will allow us to continue a very active research program at a detector, located close to the production target, where event rates are much higher than at the previous generation of neutrino beam facilities.

At Fermilab, the new neutrino facility NuMI, designed for the MINOS neutrino oscillation experiment, will be based on the Main Injector (MI) accelerator. The neutrino beams from the MI yield several orders of magnitude more events per kg-year of detector than earlier neutrino beams.

2. The Fermilab NuMI Facility

The Fermilab NuMI facility is made up of the technical beamline components including target, two magnetic focusing horns, evacuated decay pipe, monitoring devices, shielding...., the underground facilities to contain the beamline components and a large, on-site experimental detector hall $\sim$ 100 meters underground.

2.1. The NuMI Near Experimental Hall

The upstream end of the near detector hall is just over 1 km downstream of the target. This experimental hall is being constructed and completely outfitted for the MINOS near detector. The hall is 45 m long, 9.5 m wide and 9.6m high. There is a space upstream of the MINOS near detector amounting to, roughly, a cylinder 26 m long and 3m in radius for additional detector(s) which, were it desired, could use the MINOS near detector as an external muon identifier and spectrometer.

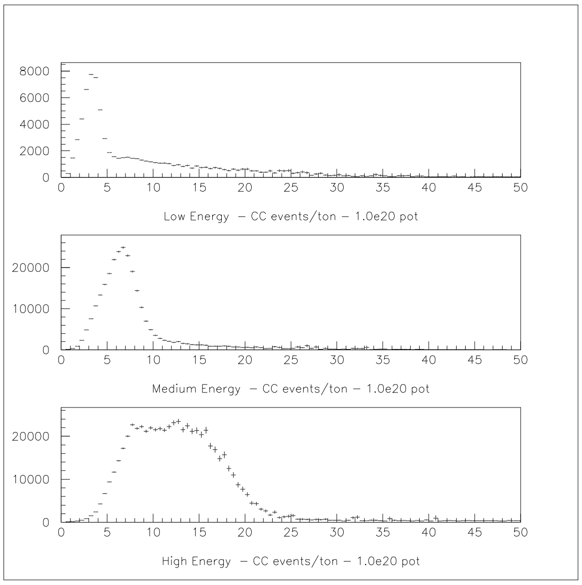

Figure 1. The neutrino event energy distribution for the three configurations of the NuMI beam corresponding to low-energy (le), medium-energy (me) and high-energy (he)

2.2. The NuMI Neutrino Beam

The neutrino energy distribution of the NuMI beam can be chosen by changing the distance of the target and second horn with respect to the first horn, as in a zoom lens. There are three standard configurations foreseen for the target and second horn called simply low-energy (le), medium-energy (me) and high-energy (he). The neutrino energy distributions are shown in Figure 1. It is now expected that the Main Injector will deliver 2.5x10^{20} POT/year at the start of MINOS running, and build up to 3.8x10^{20} POT/year after the first several years of running if the necessary funds can be obtained. The CC event rates per ton (of detector) - year at startup of MINOS in 2005 will be le - 200 K, me - 675 K and he - 1575 K. The reader should be aware that there is a potential increase of **50%** when the MI reaches the goal of 3.8x10^{20} POT/year.

For the MINOS experiment the beamline will be operating mainly in its lowest possible neutrino energy configuration to be able to reach desired low values of δm^2. However, to minimize systematics, there will also be running in the pseudo-me and pseudo-he modes (obtaind by simply varying the distance of target from the first horn and leaving the second horn fixed in the le position). For the approved MINOS run the total CC event rate would be 860 K/ton. Of this rate, 140 K/ton would be quasi-elastic, 360 K/ton would be resonance/transition events and 360 K/ton would be deep-inelastic (DIS) with W $\geq$ 2 GeV and $Q^2 \geq$ 1.0 GeV^2.

For a NuMI neutrino scattering experiment as prime user of the NuMI beam, the beamline would be run in the high-energy configuration A NuMI Neutrino Scattering Experiment, for example, running with the he-beam for a 1 year ν and a 2 years $\overline{\nu}$ period would accumulate 1575 K CC ν events/ton and 0.9 M CC $\overline{\nu}$ events/ton. Of these 0.9 M CC ν events/ton and 0.35 M CC $\overline{\nu}$ events/ton would be DIS.

The event rates for various scenarios are summarized in the following table giving events/ton-year where a "year" is defined as 2.5x10^{20} POT.

Event Rates per ton of detector

Run Period	Total CC	Elastic	DIS
MINOS: 3yr	860 K	140 K	360 K
he-ν: 1yr	1575 K	200 K	900 K
he-$\overline{\nu}$: 2yr	900 K	60 K	350 K

3. Neutrino Scattering Physics

A neutrino scattering experiment in the NuMI Near Experimental Hall will offer a unique opportunity to study a diverse array of physics topics. Most of these topics have either never been studied or the few results that do exist are plagued by large statistical and systematic errors. In addition to being significant fields of study in their own right, many of these topics are essential to help minimize the systematics of neutrino oscillation experiments.

- quasi-elastic neutrino scattering and associated form-factors
- the poorly studied resonance production region
- the intriguing region where resonance production joins deeply inelastic scattering
- parton distribution functions (pdf), particularly in the high-x_{Bj} region
- leading exponential contributions of pQCD
- $\sin^2\theta_W$ via the ratio of NC / CC as well as dσ/dy from ν - electron scattering to check the recent surprising NuTeV result [1]
- charm physics including the mass of the charm quark (m_c) to an order of magnitude better accuracy than current values, V_{cd}, s(x) and, independently, $\overline{s}$(x)
- **nuclear effects involving neutrinos. In particular are nuclear effects the same for valence and sea quarks? Are they different for u_v as compared to d_v?**
- strange particle production for V_{us}, flavor-changing neutral currents and measurements of hyperon polarization
- contribution of the spin of the strange quark through ν elastic scattering. This measurement is far more accurate and needs many fewer assumptions than charged lepton results for Δs.
- nuclear physics studies with neutrinos (complementary to JLab studies in the same kinematic range)

For this paper, the subject of nuclear effects will be addressed in more detail.

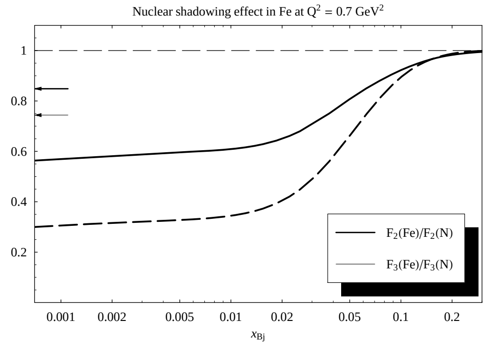

Figure 2. Expected shadowing effects off an Fe target at $Q^2 = 0.7$ GeV^2 with Kulagin's non-perturbative parton model. The arrows in the vicinity of R = 0.8 indicate the expected shadowing strength at $Q^2 = 15.0$ GeV^2

3.1. Studying Nuclear Effects with Neutrinos

Nuclear effects in DIS have been studied extensively using muon and electron beams but have only been glanced at for neutrinos in low-statistics bubble chamber experiments. A neutrino scattering program at NuMI would provide experimental conditions where a systematic, precision study of this field would be possible by using a variety of heavy nuclear targets as well as H_2 and D_2 targets. Briefly reviewing these nuclear effects as a function of x_{Bj} we find:

3.1.1. Low x: Nuclear Shadowing In the shadowing region, $x < 0.1$, there are several effects where a neutrino probe could provide different insights compared to charged lepton probes. "Shadowing" is a phenomena which occurs with nuclear targets and is characterized by the cross section per nucleon being less for larger A nuclei, such as Fe, than for smaller A nuclei such as D_2. See [2] for a recent summary of theoretical ideas on this topic.

Vector meson dominance (VMD) is the accepted explanation for shadowing in the scattering of charged leptons off nuclei (i.e. $\mu/e - A$) for Q^2 roughly $\leq 5\ GeV^2$. In essence, the incoming boson dissociates into a q-$\overline{q}$ pair which interacts with the nucleus as a meson. Due to the V-A nature of the weak interaction, it is predicted that neutrino scattering should involve not only a VMD effect but also additional contributions from axial-vector mesons such as the A_1. Other sources of nuclear shadowing (mainly in larger nuclei) involve gluon recombination from nucleons neighboring the struck nucleon that shift the parton distributions towards higher values of x. At higher Q^2, shadowing is dominated by Pomeron exchange in diffractive scattering.

A quantitative analysis by Kulagin [4] of shadowing effects in neutrino interactions predicts shadowing effects in ν - A scattering. As seen in Figure 2, which gives predictions of the ratio of scattering off Fe to scattering off D_2, shadowing effects with neutrinos are expected to be dramatically large at low Q^2 (the kinematic region of the NuMI neutrino beam) and still significant at large Q^2. Kulagin also attempts to determine the quark flavor dependence of shadowing effects by separately predicting the shadowing observed in $F_2(x, Q^2)$ (sum of all quarks) and $xF_3(x, Q^2)$ (valance quarks only). These predictions of Kulagin would be testable with the NuMI beam.

3.1.2. Mid x: Anti-shadowing and the EMC Effect Drell-Yan experiments have also measured nuclear effects and their results are quite similar to DIS experiments in the shadowing region. However, in the anti-shadowing region where R_A, the ratio of scattering off a nucleus A to scattering off of deuterium, makes a statistically significant excursion above 1.0 in DIS, Drell-Yan experiments see no effect. This could be an indication of differences in nuclear effects between valence and sea quarks as also predicted by Kulagin.

Eskola et al. [5] has quantified this difference using a model which predicts that the differences between nuclear effects in $xF_3(x, Q^2)$ and $F_2(x, Q^2)$, quantified by Kulagin in the shadowing region, should persist through the anti-shadowing region as well. More recent work by Kumano [6] supports these findings using different fitting techniques.

Based on the various theoretical explanations for the anti-shadowing and EMC effects existing today, the measured effects could be considerably different for neutrinos. Neutrino scattering results would help the theoretical understanding of these phenomena.

3.1.3. High x: Multi-quark Cluster Effects Analyses from DIS experiments of $F_2(x, Q^2)$ in the "Fermi-motion" region, $x \geq 0.7$, have used few-nucleon-correlation models and multi-quark cluster models in order to fit the data. These models boost the momentum of some quarks, which translates into a high-x tail in $F_2(x, Q^2)$ that is predicted to behave as e^{-ax}. However, fits to $\mu - C$ [7] and $\nu - Fe$ [8] have obtained two different values for the fitted constant a: $a = 16.5 \pm 0.5$ and $a = 8.3 \pm 0.7 \pm 0.7$ (systematic), respectively. This is considered surprising because of the expectation that any few-nucleon-correlation or multi-quark effects would have already saturated by carbon. A high statistics data sample, off several nuclear targets, with precise kinematic reconstruction of the Bjorken x values for each event, could go a long way towards resolving the dependence of the value of a on the nucleus and on the lepton probe.

4. A Staged Detector Concept

The detector studies for a dedicated NuMI ν scattering experiment are at a very early stage. In order to perform the full spectrum of physics outlined in this paper, the target and detector must eventually be able to:

- identify muons and measure their momentum with high precision
- identify and measure the energy of protons
- achieve a high level of rejection against tracks which fake neutral current scattering, such as neutron scattering events
- measure the energy of both the hadronic and electromagnetic shower with reasonable precision
- accommodate other nuclear targets.
- incorporate particle identification for complete reconstruction of final states

These goals can be readily met in a staged approach to detector development and installation. Both for running in a parasitic mode with the MINOS experiment and for an initial he-configuration ν exposure, the physics goals can be met by a comparatively simple active target/detector [9] consisting essentially of solid scintillator interspersed with occasional planes of variable A target. The detector would have the approximate overall dimensions of a cube 2.0 m on a side. Significant granularity could be achieved by the use of 2.0 m long by 2 cm x 2 cm strips of plastic scintillator(CH) with a fiber down the center of the strip for readout. Recent work at the Fermilab Scintillator R&D Facility has shown that using light division across triangularly shaped scintillator strips of this size can yield measuring precisions of a few mm. The orientation of the scintillator strips are alternated so that tracking can be performed. The detector overall mass would be around 8 metric tons with somewhat over 3 tons of scintillator in a fiducial volume defined as r $\leq$ 0.8m and 150 cm long. Readout would be performed with VLPC technology most recently developed at Fermilab for the D0 experiment.

The downstream end of this detector would be placed as close as possible to the upstream face of the MINOS near detector in order to use the magnetic field and steel of the MINOS near detector as a muon identifyer and spectrometer for the energetic forward going muons. Side muon ID/spectrometers (EMI) consisting of several planes of scintillator interspersed with permanent magnet steel planes would be installed surrounding the four sides of the detector to increase acceptance of the low energy muons and measure the hadronic energy leaving the sides of the central detector.

With such a detector, for the initial energy-dependent MINOS run given earlier, two such cycles (32 months running) would result in **2.6 M events** in the fiducial volume of the scintillator while for a 1 year he-configuration ν run, the corresponding statistics would be **4.9 M events**.

4.1. Measuring Nuclear Effects

For the study of nuclear effects a selection of nuclear targets would be installed within the scintillator based detector. As an example, 1 ton of C, Fe and Pb were included in the simulation as eleven planes of pure C, three planes of Fe and 2 planes of Pb. The following table summarizes the event rates during the initial MINOS run and a subsequent he ν run for the scintillator plus nuclear target detector concept described here:

CC Event Rates		
Target	MINOS 2-cycle	1 year he ν
CH	2.6 M	4.9 M
C	860 K	1575 K
Fe	860 K	1575 K
Pb	860 K	1575 K

Somewhat over 20% of the above event rates have $x_{Bj} \leq 0.10$ for studies of shadowing. The (approximate) statistical accuracy for measurements of the nuclear effects in the ratios of Fe to C events at small x (shadowing region) are summarized in the following table. The columns designated DIS implies that a cut has been made to keep only events with W $\geq$ 2.0 and $Q^2 \geq 1.0$. For the MINOS DIS analysis, the first three bins could be combined into two bins to reduce the statistical errors.

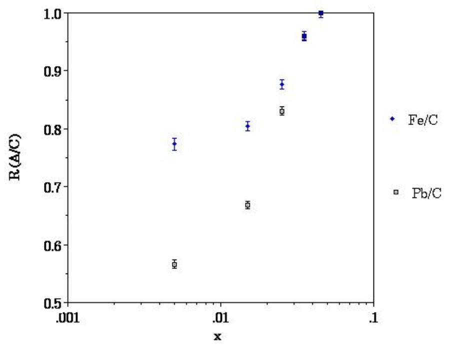

Figure 3. Kulagin's predicted ratio of shadowing effects off Fe and C targets with the expected errors from all events from the MINOS run

Ratio Fe/C: $\sim$ Statistical Errors				
x_{Bj}	MINOS 2-cycle	MINOS DIS	he ν 1 year	he ν DIS
0.0 - .01	1.8 %	xxx	1.3 %	xxx
.01 - .02	1.4	10 %	1.0	9 %
.02 - .03	1.3	6	1.0	5
.03 - .04	1.2	4	≤ 1	3.2
.04 - .05	1.1	3	≤ 1	2.1
.05 - .06	1.1	2.6	≤ 1	1.7
.06 - .07	1.0	2.3	≤ 1	1.4

Assuming the magnitude of shadowing as predicted by Kulagin, the measured ratio of Fe/C, with statistical errors corresponding to the data accumulated during the MINOS run, would be as in Figure 3. The ratios plotted are for all events. The statistical errors would increase as indicated in the above table when making a DIS cut.

The statistics from the first 3-year MINOS run would be adequate to perform many of the physics topics listed in this paper although some would be limited by the kinematic reach of the neutrino beam energies used for MINOS running. In addition, all studies involving $\overline{\nu}$ statistics would be impossible with only the approved MINOS (ν) exposure. To realize the **full potential** of the NuMI facility for a ν scattering experiment, the impressive statistics and kinematic reach of a he-beam ν and $\overline{\nu}$ runs would be required.

In a subsequent stage it would also be most beneficial, for all physics topics of interest, to have a low-A target, preferably H_2 or D_2. An investigation of the technical and safety challenges of such a target is currently underway at Fermilab and a recent report indicates that there are no real technical challenges in fabricating or efficiently operating a large LH_2 or LD_2 target. The main effort (and expense) for such a facility would be in satisfying safety requirements. For a fiducial volume with r = 80 cm. and l = 150 cm. we would expect 350 K CC events in LH_2 and 800 K CC events in LD_2 per year of he-ν running. With such samples of LH_2 and/or LD_2, the statistical errors in shadowing studies would be:

Ratios(he, 1 year, DIS): $\sim$ Stat. Errors

x_{Bj}	Fe/C	Fe/LD_2
.01 - .02	9 %	11 %
.02 - .03	5	6
.03 - .04	3	4
.04 - .05	2	3
.05 - .06	1.7	2
.06 - .07	1.4	1.7

This large sample of events would allow extraction of the nuclear effects on the individual structure functions F_2 and xF_3 via the ratios of Pb and Fe to D_2.

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