Nuclear Physics Studies at Fermilab using the new Proton Driver

Weiren Chou and Jorge G. Morfín
Fermilab

1 Introduction

Fermilab is currently evaluating the physics potential of replacing the present Booster in the Fermilab accelerator chain LINAC - Booster - Main Injector - Tevatron with a much improved accelerator called the Proton Driver. The design of this Proton Driver has been completed and the document entitled "The Proton Driver Design Study" describes in detail the design of this new brighter booster as a complete functional replacement for the present Booster. This document will be published as a technical memo FERMILAB-TM-2136 and it can also be downloaded from the web: *http://www-bd.fnal.gov/pdriver/reports.html.*

Using the much increased output of the Proton Driver and the consequent increased intensity of the Main Injector and the Tevatron, a study has begun to determine what new physics topics are now possible and what current measurements can be improved with the increased intensity of the accelerator chain.

This document is a short summary of the technical design of the Proton Driver and an outline of some of the many neutrino physics topics which might be of interest to the Nuclear Physics Community. There are, of course, many physics topics involving the high intensity 16 GeV protons from the Proton Driver or the 120 GeV protons from the Main Injector that might be of considerable interest to the nuclear physics community. These topics will be the subject of a separate document. **Our specific goal is to attract members of the nuclear physics community to join our Proton Driver Physics study group on the physics potential of future BooNe and NuMI neutrino experiments [1]. A likely outcome of this study is the formation of a collaboration for a second generation NuMI experiment to cover the physics topics outlined below plus other topics of interest to both the high energy and nuclear physics communities**.

2 Technical Description of the Proton Driver

The Proton Driver is a rapid-cycling (15 Hz), high-intensity (3×10^{13} protons per pulse), 1 MW 16-GeV synchrotron. It serves a number of purposes in the Fermilab hadron program. In the near term, it replaces the present Booster and increases the proton beam intensity in the Main Injector by a factor of four, thereby providing an upgrade path for NuMI and other 120 GeV fixed target programs. It also helps increase the Tevatron collider luminosity after the antiproton source takes necessary measures to accommodate more antiprotons. The Proton Driver also opens the avenue for new physics programs based on its stand-alone capabilities as a source of intense proton beams. The beam power of the Proton Driver is a factor of twenty higher than that of the present Booster. It can be employed for the production of high-intensity secondary particle beams of pions, kaons, muons, neutrons and neutrinos. In the long term, the Proton Driver could serve a neutrino factory and/or a muon collider by generating intense short muon bunches from a target. The design also allows an upgrade path to a 4 MW proton source by adding a 600 MeV linac and a 3 GeV Pre-Booster at some late time (called Phase II).

The Phase I, namely, a 1 MW Proton Driver, has two stages. Stage 1 provides a maximum beam energy of 12 GeV with a 53 MHz rf system, whereas Stage 2 increases the beam energy to 16 GeV with a new 7.5 MHz rf system. The main reason for this staged design is the following: In Stage 1, there will be no neutrino factory for the Proton Driver to serve. The beam energy and rf frequency are chosen to best fit the Main Injector. In Stage 2, however, it is envisioned that the Proton Driver will serve both the Main Injector and a neutrino factory. The latter requires a small number of proton bunches and more beam power.

The main parameters of the Proton Driver in Stage 1 and 2 are listed in Table 1. As a comparison, the parameters of the present Booster are also listed. Table 2 lists the parameters of Phase II, a future upgrade to 4 MW.

Table 1: Parameters of Present, Stage 1 and Stage 2

	Present	Stage 1 (MI)	Stage 2 (MI+ν-fact)
Linac (operating at 15 Hz)			
Kinetic energy (MeV)	400	400	400
Peak current (mA)	40	60	60
Pulse length (μs)	25	90	90
H^- per pulse	6.3×10^{12}	3.4×10^{13}	3.4×10^{13}
Average beam current (μA)	15	81	81
Beam power (kW)	6	32	32
Booster (operating at 15 Hz)			
Extraction kinetic energy (GeV)	8	12	16
Protons per bunch	6×10^{10}	2.4×10^{11}	1.7×10^{12}
Number of bunches	84	126	18
Total number of protons	5×10^{12}	3×10^{13}	3×10^{13}
Normalized transverse emittance (mm-mrad)	15π	60π	60π
Longitudinal emittance (eV-s)	0.1	0.1	0.4
RF frequency (MHz)	53	53	7.5
Extracted bunch length σ_t (ns)	0.2	1	1
Average beam current (μA)	12	72	72
Target beam power (MW)	0.1	0.9	1.2

Note: Although originally designed for 15 Hz operation, the present Booster has never run at 15 Hz in continuous mode. In the past it used to run at 2.5 Hz. In the near future it will run at 7.5 Hz for the MiniBooNE experiment.

Table 2: Parameters of Present, Phase I and Phase II

	Present	Phase I (MI+ν-factory)	Phase II ($\mu\mu$-collider)
Linac (operating at 15 Hz)			
Kinetic energy (MeV)	400	400	1000
Peak current (mA)	40	60	80
Pulse length (μs)	25	90	200
H^- per pulse	6.3×10^{12}	3.4×10^{13}	1×10^{14}
Average beam current (μA)	15	81	240
Beam power (kW)	6	32	240
Pre-booster (operating at 15 Hz)			
Extraction kinetic energy (GeV)			3
Protons per bunch			2.5×10^{13}
Number of bunches			4
Total number of protons			1×10^{14}
Normalized transverse emittance (mm-mrad)			200π
Longitudinal emittance (eV-s)			2
RF frequency (MHz)			7.5
Average beam current (μA)			240
Beam power (kW)			720
Booster (operating at 15 Hz)			
Extraction kinetic energy (GeV)	8	16	16
Protons per bunch	6×10^{10}	1.7×10^{12}	2.5×10^{13}
Number of bunches	84	18	4
Total number of protons	5×10^{12}	3×10^{13}	1×10^{14}
Normalized transverse emittance (mm-mrad)	15π	60π	200π
Longitudinal emittance (eV-s)	0.1	0.4	2
RF frequency (MHz)	53	7.5	7.5
Extracted bunch length σ_t (ns)	0.2	1	1
Average beam current (μA)	12	72	240
Target beam power (MW)	0.1	1.2	4

3 Neutrino Physics

The neutrino program at Fermilab has always been strong and at the forefront of both QCD and Electroweak research. The Lab E detector, used by both the CCFR and NuTeV collaborations, was a rich source of significant results in the study of $\nu - Fe$ interactions. With a neutrino beam using the Tevatron 800 GeV protons, the energy of the neutrino beam was the highest yet created by an accelerator. However, the 60 second cycle time and limited protons on target restricted the accumulation of statistics even with the multi-hundred ton Lab E detector.

The future of neutrino physics at Fermilab, instead of being based on the Tevatron, will be based on the two lower energy accelerators at Fermilab; the Booster and the new Main Injector (MI). Although the neutrinos from these accelerators do not have the energy and thus kinematic reach of the TeVatron neutrino beam, they do yield several orders of magnitude more events per ton-year than the TeVatron neutrino beam. This highlights the major improvement of the Booster and MI neutrino experiments over the TeVatron experiments. One could, in principle, now perform statistically significant experiments with light targets such as H_2 and D_2 . These neutrino beams for both the Booster and MI are currently being constructed for the MiniBooNe and MINOS experiment respectively and will be available for experiments within the next three years. That both of these experiments are to study neutrino oscillations points out the second advantage of future neutrino experiments at Fermilab; an excellent knowledge of the neutrino beam will be required to reduce the beam-associated systematics of the oscillation result. This knowledge of the neutrino spectrum will also reduce the beam systematics in the measurement of non-oscillation phenomena.

3.1 The Booster Neutrino Program

There are many representatives of the Nuclear Physics community on the MiniBooNe Booster neutrino oscillation experiment who have already informed the community of the Booster Neutrino program. In addition, some of the potential BooNe non-oscillation physics topics were covered at the Seattle Neutrino Town Meeting [2].

Some of the topics to be examined as part of the Proton Driver Physics Study now underway include [3]:

- Quasi-elastic scattering; the strange-spin of the nucleon,
- Charged current ν_μ scattering; the axial-vector dipole mass,
- Neutral Current π^0 production; the helicity structure of the weak neutral current,
- $\nu_\mu e^-$ elastic scattering at low-Q^2; the neutrino magnetic moment.

3.2 The Main Injector Neutrino Facility - NuMI

The Main Injector, commissioned in 1999, replaced the old Main Ring to increase the luminosity of Collider Experiments and to provide a Fixed Target program that could operate concurrently with the Collider program. The first Main Injector fixed target experiment is the neutrino oscillation experiment MINOS in the Main Injector neutrino beam.

The MI neutrino beam project, called NuMI, uses two parabolic horns to focus mesons coming from a 2 λ_I target. Since a parabolic horn focuses as if it were a lens, the positions of the meson production target and the second (downstream) horn can be moved with respect to the first horn as with a zoom lens to provide a range of focused neutrino energies. Details of the neutrino event rates at the MINOS near hall location, including the increased event rates due to the "hadronic hose" recently approved for installation, for three typical beam configurations labeled low-energy (le), medium-energy (me) and high-energy (he) can be found as figures 1, 3 and 5 of NuMI note NuMI-B-700 downloadable from *http://www.hep.anl.gov/ndk/hypertext/numi_notes.html.*

For the first run of the beam with the MINOS neutrino oscillation experiment, the beam will be run in its low-energy (le) configuration to extend the reach of the experiment to low values of δm^2. Excluding a high energy tail coming from fast-forward unfocused pions, the average neutrino event energy in the le-configuration is 3.5 GeV and the expected event rate is around 300,000 per ton-year at the MINOS near detector position. For a second generation NuMI experiment, the beam could be run in the high-energy configuration with an average neutrino event energy of 15 GeV and an event rate of 3,000,000 per ton-year. **The proposed new proton driver, which could be ready for such a second generation NuMI experiment, would increase this event rate to order 10^4 events per KG-year.** This increased neutrino energy also extends the reach in the kinematic variables x and y to cover regions where interesting nuclear effects in the measurement of structure functions are expected.

In addition to the dramatically increased neutrino flux, an advantage of the NuMI facility will be the existence of a near detector hall just over 1 Km from the target with full utilities and a space roughly 20 m long and 4 m in radius available for a new experimental detector. The MINOS near detector, consisting of solid scintillator planes with fiber readout sandwiched between 2.5 cm thick steel plates, occupies the downstream 18 m of the hall and could be used as an external muon identifier for the more energetic muons exiting an upstream detector.

3.3 NuMI Physics: Extracting Parton Distribution Functions

With intensities of 3,000 events/kg-year, or 10,000 events/kg-year with the new Proton Driver, and energies in the 1 - 40 GeV range, physics topics ranging from quasi-elastic neutrino scattering through resonance production and the intriguing region where resonance production joins deeply inelastic scattering can be studied with minimal statistical and systematic errors off a variety of targets. The following is a summary of work found in more detail in [4].

The study of the partonic structure of the nucleon, using the neutrino's weak probe, could complement the on-going study of this subject with electromagnetic probes at Jlab. The unique ability of the neutrino to "taste" only particular flavors of quarks enhances any study of parton distribution functions.

With the high statistics foreseen at NuMI with the proton driver as well as the special attention to minimizing neutrino beam systematics, it should be possible for the first time to determine the separate structure functions $2F_1^{\nu N}(x,Q^2)$,$2F_1^{\bar{\nu} N}(x,Q^2)$, $F_3^{\nu N}(x,Q^2)$ and $F_3^{\bar{\nu} N}(x,Q^2)$ where N is an isoscalar target. In leading order QCD (used for illustrative purposes) these four structure functions are related to the parton distribution functions by:

$$\begin{aligned}
2F_1^{\nu N}(x,Q^2) &= u(x)+d(x)+s(x)+\bar{u}(x)+\bar{d}(x)+\bar{c}(x) \\
2F_1^{\bar{\nu} N}(x,Q^2) &= u(x)+d(x)+c(x)+\bar{u}(x)+\bar{d}(x)+\bar{s}(x) \\
xF_3^{\nu N}(x,Q^2) &= u(x)+d(x)+s(x)-\bar{u}(x)-\bar{d}(x)-\bar{c}(x) \\
xF_3^{\bar{\nu} N}(x,Q^2) &= u(x)+d(x)+c(x)-\bar{u}(x)-\bar{d}(x)-\bar{s}(x)
\end{aligned} \tag{1}$$

Note that taking differences between these structure functions would then allow extraction of individual parton distribution functions in a given x, Q^2 bin:

$$\begin{aligned}
2F_1^{\nu N} - 2F_1^{\bar{\nu} N} &= [s(x)-\bar{s}(x)]+[\bar{c}(x)-c(x)] \\
2F_1^{\nu N} - xF_3^{\nu N} &= 2[\bar{u}(x)+\bar{d}(x)+\bar{c}(x)] \\
2F_1^{\bar{\nu} N} - xF_3^{\bar{\nu} N} &= 2[\bar{u}(x)+\bar{d}(x)+\bar{s}(x)] \\
xF_3^{\nu N} - xF_3^{\bar{\nu} N} &= [\bar{s}(x)+s(x)]-[\bar{c}(x)+c(x)]
\end{aligned} \tag{2}$$

As we increase the order of QCD and allow gluons into consideration we need to bring in global fitting techniques into the extraction of the parton distribution functions. However, if the statistical and systematic errors can be kept manageable, the ability to isolate individual parton distribution functions will be dramatically increased by measuring the full set of separate ν and $\bar{\nu}$ structure functions.

3.4 NuMI Physics: 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. High statistics neutrino experiments have, to date, only been possible using heavy nuclear targets such as iron-dominated target-calorimeters and, for these targets, nuclear effects in $\nu - N$ interactions have typically been considered as problems to overcome rather than as a source of physics insights. A non-oscillation neutrino program at NuMI would provide experimental conditions where a great deal of interesting knowledge could be added to this field by using a variety of heavy nuclear targets as well as H_2 and D_2 targets.

Nuclear studies at NuMI could use a detector dedicated to nuclear studies similar, for example, to the geometry of the Fermilab E-665 Tevatron muon experiment. It could consist of a liquid H_2 or D_2 target followed by targets with different atomic weights(A), interspersed with tracking chambers, and then by appropriate calorimetry and muon identification and momentun measurement detectors. The challenge, of course, is designing a cryogenic target that is massive enough to accumulate sufficient statistics while allowing tracking.

Looking in a bit more detail at a few physics topics as a function of x_{Bj}:

3.4.1 Low x: PCAC and Nuclear Shadowing - the HERMES Surprise

In the shadowing region, $x < 0.1$, there are several effects where a neutrino probe could provide different insights compared to charged lepton probes. Considering first the limit as $Q^2 \rightarrow 0$, the vector current is conserved and goes to zero but the axial-vector part of the weak current is only partially conserved (PCAC) and $F_2(x, Q^2)$ approaches a non-zero constant value as $Q^2 \rightarrow 0$. According to the Adler theorem [7], the cross section of $\nu_\mu - N$ can be related to the cross section for $\pi - N$ at $Q^2 = 0$. CCFR has made initial measurements [6] of this effect with neutrinos off an Fe target with no attempt to correct for possible neutrino specific nuclear effects.

The region of vector meson dominance (VMD) is reached in nuclear scattering of charged leptons (i.e. $\mu/e - A$ scattering) in the low-x shadowing regime as Q^2 increases from 0 but remains below 10 GeV^2.

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. Further, there should be additional non-perturbative effects that appear as nuclear shadowing (mainly in larger nuclei) and which involve gluon recombination from nucleons neighboring the struck nucleon that shift the parton distributions towards higher values of x. A quantitative analysis of neutrino shadowing effects by Kulagin [8] used a non-perturbative parton model to predict shadowing effects in ν - A scattering. At $Q^2 = 5\mathrm{GeV}^2$, he predicts the shadowing in ν - A scattering to be either equal to or slightly less than in μ/e - A scattering. He 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). The predictions of Kulagin should be testable with the NuMI beam.

Shadowing had been studied extensively by both electron and muon experiments when the HERMES experiment recently performed their shadowing analysis [9]. Looking at cross section ratios for deep-inelastic scattering from ^{14}N and ^{3}He with respect to ^{2}H over a range in x between 0.013 and 0.65, and Q^2 from 0.5 to 15 GeV^2

and comparing their data to measurements performed by NMC, E665, and SLAC on ^4He and ^{12}C, they found significant differences for x $\leq$ 0.06 and Q^2 $\leq$ 1.5 GeV^2. The observed difference is attributed to an A-dependence of the ratio (R = σ_L / σ_T) of longitudinal to transverse deep-inelastic scattering cross sections at low x and low Q^2. This kinematic region would be covered by a second generation NuMI experiment using the he-beam configuration.

3.4.2 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 difference in nuclear effects between valence and sea quarks.

Eskola et al. [10] 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.

3.4.3 High x: Multi-quark Cluster Effects, Higher Twists and Elastic Scattering

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 μC and νFe 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 was 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 with the NuMI beam 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.

In addition to these multi-quark effects, there is interesting physics in the region of high x which can be characterized as the interface between perturbative and non-perturbative QCD. This is a region that requires much additional study with both electroproduction and the weak current of neutrino nucleon interactions. A high statistics neutrino/antineutrino exposure in H_2 and D_2 provides the most direct way of studying this rich region of phase space.

The uncertainties at high x in current nucleon parton distribution functions are of two types: the ratio of the light quark PDF's, $d(x)/u(x)$, as $x \to 1$ and the role of leading power corrections (higher twist) in the extraction of the high x behavior of the quarks.

Analyses of present leptoproduction data sets that used hydrogen and deuterium targets have been unable to precisely pin down the high-x behavior of $d(x)/u(x)$. Besides the statistical and experimental uncertainties in the existing data sets, a complication with past experimental results was the need to model nuclear binding effects in the deuterium target which was used. These issues could be avoided with a high statistics exposure to a H_2 target which could directly measure the $d(x)/u(x)$ ratio in protons as $x \to 1$ from the ratio of neutrino-proton to antineutrino-proton cross sections. Such a measurement would require only a small correction for the residual sea quark contributions at high x.

The measurement of quark densities at high x is closely related to the question of the leading power corrections known as "higher twist effects". The n^{th} order higher twist effects are proportional to $1/Q^{2n}$ and reflect the fact that quarks have transverse momentum within the nucleon and that the probe becomes larger as Q^2 decreases, thus increasing the probability of multi-quark participation in an interaction. As was the case with the d/u ratio, different analyses of higher twist corrections in current data leave some unresolved issues that would benefit from with new experimental information.

The only measurements of higher-twist term in neutrino experiments have been two low-statistics bubble chamber experiments: in Gargamelle [5] with freon and in BEBC with NeH_2. Both bubble chamber analyses are complicated by nuclear corrections at high-x. However, both analyses found a twist-4 contribution that is smaller in magnitude than the charged leptoproduction analysis and, most significantly, is preferentially negative.

Finally, recent studies [11] of neutrino proton elastic scattering has shown that it should be possible to extract the strange vector and axial-vector form factors of the proton. A high statistics exposure of $\nu - H_2$ should add considerable knowledge of the strange component of the proton.

3.5 NuMI Physics: Neutrino - Polarized Target Scattering

A unique feature of NuMI could be the availability of sufficiently intense beams to allow measurements of neutrino scattering off nucleons in polarized targets. This will depend critically on the mass and transverse dimension of available polarized targets. If feasible, this would provide access to the polarized nucleon structure functions for neutrino-nucleon scattering and should be able to answer some currently unresolved questions about the spin structure of the nucleon.

The polarized structure functions $g_1(g_2)$ and g_3 have quark spin content corresponding to the quark content of the parity conserving and parity violating unpolarized structure functions $F_1(F_2)$ and F_3, respectively.

To date, the only experiments to have addressed this question have been charged lepton - polarized target DIS experiments running at energies where only photon exchange is relevant. Thus, only the parity conserving polarized structure functions g_1 and g_2 have been studied so far.

References

[1] The Proton Driver Physics study group on non-oscillation neutrino physics is led by Bonnie T. Fleming, Colombia University and Jorge G. Morfín, Fermilab.

[2] J. Bahcall et al., "Nuclear physics neutrino pretown meeting: Summary and recommendations," e-Print Archive: nucl-th/0011014.

[3] This list provided by Rex Tayloe, University of Indiana, who will be studying future BooNe neutrino experiments as part of the Proton Driver Non-oscillation Neutrino Physics Study.

[4] C. Albright et al., "Physics at a Neutrino Factory," FERMILAB-FN-692, Aug 2000. 133pp. e-Print Archive: hep-ex/0008064. and I. Bigi et al. "The Potential for Neutrino Physics at Muon Colliders and Dedicated High Current Muon Storage Rings", submitted to Physics Reports, Jan. 2001.

[5] H. Deden and et al., [Gargamelle Neutrino Collaboration], "Experimental Study Of Structure Functions And Sum Rules In Charge Changing Interactions Of Neutrinos And Anti-Neutrinos On Nucleons," Nucl. Phys. **B85**, 269 (1975).

[6] B.T. Fleming et al., [CCFR Collaboration and NuTeV Collaboration] "A first Measurement of the Low x - Low Q^2 Structure Functions in Neutrino Scattering," Nov 2000. e-Print Archive: hep-ex/0011094.

[7] S. L. Adler, "Sum Rules Giving Tests Of Local Current Commutation Relations In High-Energy Neutrino Reactions," Phys. Rev. 143, 1144 (1966).

[8] S. A. Kulagin, "Nuclear shadowing in neutrino deep inelastic scattering," hep-ph/9812532.

[9] K. Ackerstaff et al. [HERMES Collaboration], "Nuclear effects on R = sigma(L)/sigma(T) in deep inelastic scattering," Phys. Lett. B **475**, 386 (2000). e-print Archive: hep-ex/9910071.

[10] K. J. Eskola, V. J. Kolhinen, P. V. Ruuskanen and C. A. Salgado, "Nuclear parton distributions: A DGLAP analysis," Nucl. Phys. **A661**, 645 (1999) e-Print Archive: hep-ph/9906484.

[11] G. T. Garvey, W. C. Louis, D. H. White, "Determination of the Proton Strange Form-factors from Neutrino P Elastic Scattering" Phys. Rev. C48, 761, (1993)