Physics Prospects with an Intense Neutrino Experiment

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Abstract. With new forthcoming intense neutrino beams, for the study of neutrino oscillations, it is possible to consider other physics experiments that can be done with these extreme neutrino fluxes available close to the source.

INTRODUCTION

The objectives of my talk are to bring to the attention of both the particle and nuclear physics communities the unique physics potential that an intense neutrino beam experiment might be able to perform, other than that of neutrino oscillation which is covered elsewhere in these proceedings [1]. The list of non-oscillation physics is large and will not be completely covered in detail in such a short writeup, but the hope is that it might interest physicists, both theoretical and experimental, to contribute their ideas to help formulate a new experiment that can take full advantage of the intense neutrino beams planned in the NuMI project at Fermilab [2] and eventually the muon collider prototype storage ring [3] which might be located at Fermilab along the NuMI beamline direction.

PHYSICS PROSPECTS

Possible physics from an intense neutrino beam are:

Scattering: The first such experiments were performed by Rutherford with alpha scattering which showed the nuclei exists as a concentrated center of positive charge, while direct evidence of the quarks themselves came from experiments using the highest possible energy electrons to probe the nucleon structure. Muon scattering experiments have also contributed similar results, as well as offered a more massive probe. Furthermore, greatly improved statistics of electron scattering reactions are now being done at CEBAF. The physics of these experiments aim to measure structure functions with high precision. This is done by measuring the

electron scattering cross-section:

$$\frac{d^2\sigma}{d\Omega dE'} = \frac{4\alpha^2(E')^2}{Q^4}cos^2(\theta/2) \times [\frac{F_2(x,Q^2)}{(E-E')} + \frac{2F_1(x,Q^2)}{M}tan^2(\theta/2)] \tag{1}$$

Where $\alpha = 1/137$, M is the proton rest mass, E is the electron energy before and E' after the scattering, θ is the electron scattering angle, and the Bjorken scaling variable is $x \equiv \frac{Q^2}{2M(E-E')}$. With neutrino scattering the expression changes a little: $\frac{4\alpha^2(E')^2}{Q^4}$ becomes $\frac{G^2}{2\pi}$ where G is the Fermi constant of weak coupling, and another structure function F_3 is needed because of parity violation. Neutrino scattering experiments are capable of measuring in detail the internal structure of the nucleon threw such experiments, with the advantage that the neutrino interactions are purely weak processes. They too can look towards further improvements with higher statistics. Eventually with a sufficiently large data sample that can permit the data to be separated into ν and $\bar{\nu}$ this can be used to study the similarities between quarks and antiquarks.

Strangeness Production: The most interesting new measurement would be strange particle production by neutrino interactions. This is suppressed by a factor of $tan^2\theta_c$ (where θ_c is the Cabibbo mixing angle) and can only be done once an intense neutrino source is available with an experiment capable of identifying strange particles. With a small dedicated experiment of good resolution, events can be seen of the charged current (CC) and neutral current (NC) type:

$$\bar{\nu}_l + p^+ \rightarrow l^+ + \Lambda^0$$
$$\rightarrow l^+ + \Sigma^0$$
$$\rightarrow l^+ + \pi^0 + \Lambda^0$$
$$\rightarrow l^+ + \pi^0 + \Sigma^0$$
$$\rightarrow l^+ + K^- + p^+$$
$$\vdots$$
$$\bar{\nu}_l + n^0 \rightarrow l^+ + \Sigma^-$$
$$\rightarrow l^+ + \pi^- + \Lambda^0$$
$$\rightarrow l^+ + \pi^0 + \Sigma^-$$
$$\rightarrow l^+ + K^- + \Lambda^0$$
$$\vdots$$

$$\bar{\nu} + p^+ \rightarrow \bar{\nu} + \Sigma^+ \qquad SCNC$$
$$\rightarrow \bar{\nu} + \pi^0 + \Sigma^+ \qquad SCNC$$
$$\rightarrow \bar{\nu} + K^0 + \Sigma^+$$
$$\rightarrow \bar{\nu} + K^0 + p^+ \qquad SCNC$$
$$\rightarrow \bar{\nu} + K^+ + n^0 \qquad SCNC$$
$$\vdots$$
$$\bar{\nu} + n^0 \rightarrow \bar{\nu} + \Lambda^0 \qquad SCNC$$
$$\rightarrow \bar{\nu} + \Sigma^0 \qquad SCNC$$
$$\rightarrow \bar{\nu} + K^0 + \Lambda^0$$
$$\rightarrow \bar{\nu} + K^0 + \Sigma^0$$
$$\vdots$$

To date only a handful of experiments have measured a few of these reactions, all with bubble chambers where the particle interaction and secondary particles produced could be explicitly identified. The best results and only cross sections measured is from the CERN-PS Gargamelle bubble chamber experiment [4] with 15 events of Λ^0 CC production at 2×10^{-40} cm^2/nucleon; while 7 events exist from the ZGS bubble chamber which includes one neutral current strange particle production event [5]. More recent experiments of the 80s and 90s have not been able to measure

such interactions because they use large dense detectors to increase their neutrino interaction rate. With the advent of intense neutrino beams this can be over come by using a single thin target with a high precession experiment downstream to identify all of the secondary particles. Not only would such an experiment be able to measure strange particle production cross sections for charged and neutral current, but the comparison of the two could give an independent measurement of the weak mixing angle for a few channels, and is also possible to improve the main interactions by explicitly removing these strange particle production reactions from the sample. Table 1 lists the total neutrino and antineutrino interaction rate, as well as the expected rate of Λ^0 production in the NuMI medium energy neutrino beam. Some of the NC interactions are forbidden and if seen at a low level would be an indication of strangeness changing neutral currents (SCNC) which is a worthy physics objective. Also the production of hyperons can permit a study of hyperon polarization when produced by neutrinos, the polarization of hyperons in fixed target experiments by a proton beam was originally a surprise and is still theoretically unexplained [6].

TABLE 1. Neutrino interactions expected per year in a solid target 2.5 cm thick and 1x1 m^2, or for liquid target with a volume of 10 m^3. The Lambda yield is for the reaction $\bar{\nu}_\mu + p \rightarrow \mu^+ + \Lambda^0$.

target	ν interactions/year	$\bar{\nu}$ interactions/year	Lambda yield/year
Fe	1.0 M	0.25 M	40 k
C	0.3 M	75 k	12 k
W	2.5 M	0.63 M	110 k
H$_2$	2.2 M	0.55 M	90 k
D$_2$	5.0 M	1.25 M	250 k

Hyperon beta decays $A \rightarrow B \, e^- \, \bar{\nu}_e$ are important to study for their weak decay form-factors which give an understanding of their underlying structure [7]. In the V-A formulation the transition amplitude is:

$$M = \frac{G}{\sqrt{2}} < B|J^\lambda|A > \bar{u}_e \gamma_\lambda (1 + \gamma_5) u_\nu \tag{2}$$

The V-A hadronic current can be written as:

$$< B|J^\lambda|A >= \mathcal{C} \, i \, \bar{u}(B) \quad [\quad f_1(q^2)\gamma^\lambda + f_2(q^2)\frac{\sigma^{\lambda v}\gamma_v}{M_A} + f_3(q^2)\frac{q^\lambda}{M_A} +$$

$$[\quad g_1(q^2)\gamma^\lambda + g_2(q^2)\frac{\sigma^{\lambda v}\gamma_v}{M_A} + g_3(q^2)\frac{q^\lambda}{M_A}] \, \gamma_5 \quad]u(A) \tag{3}$$

where $\mathcal{C}$ is the CKM matrix element, and q is the momentum transfer. There are 3 vector form factors: f_1 (vector), f_2 (weak magnetism) and f_3 (an induced scaler); plus 3 axial-vector form factors: g_1 (axial vector), g_2 (weak electricity) and g_3 (an induced pseudo-scaler). This is also possible to study with neutrino interactions that produce hyperons, because the hyperon's decay itself has a self analyzing power

of the polarization. To obtain a large and clean data sample such measurements can be unambiguous, avoiding the common problem of the missing neutrino which introduces multiple solutions and missing momentum.

Comparison: The production of strangeness from nucleon scattering using electrons or photons started in the 50s, but there is yet no comprehensive theory [8]. This data is modeled by many theorists, but the models only work for the explicit interaction it was developed for. The final goal is to have a description of all of the underlying reaction mechanisms for strangeness production, and this is far from attained, especially since the strangeness production by neutrino scattering are a grand total of only 26 events: 15 from one experiment, 7 from another and a few other experiments with one event each. However, an important message from the electron and photon experiments doing similar studies is the importance to investigate simultaneously all production channels [9]:

$$\gamma + p^+ \rightarrow K^+ + \Lambda^0 \qquad\qquad e^- + p^+ \rightarrow e^- + K^+ + \Lambda^0$$
$$\rightarrow K^+ + \Sigma^0 \qquad\qquad\qquad \rightarrow e^- + K^+ + \Sigma^0$$
$$\rightarrow K^0 + \Sigma^+ \qquad\qquad\qquad \rightarrow e^- + K^0 + \Sigma^+$$
$$\vdots \qquad\qquad\qquad\qquad\qquad \vdots$$
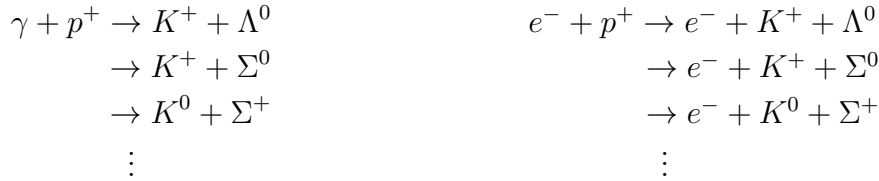
This is not a comprehensive list, other strange particle production experiments have also been done with charged mesons: $\pi^\pm$ and $K^\pm$. Plus these reactions can be expanded to more complicated ones, but it is the simple processes that are most interesting. By extending these studies to include neutrino scattering experiments of strange particle production, it would give the ability to expand our understanding of the mechanism, aid in improving the underlying nucleon, hyperon and strange meson structure, and the best improvement will be the ability to compare what is found here with that of electromagnetic interactions. This is promising to expand our knowledge of the quark sea in the nucleon.

Target Dependency: The most elementary particle structure information will come from the simplest targets which is the lightest elements: hydrogen. While neutrino scattering off of the atomic shell electron with high statistics would be useful with both CC and NC interactions. However, slightly more complicated reactions with deuterium, tritium, ^{3}He and ^{4}He are also useful. For example the deuterium data could be combined with the hydrogen results to yield the neutron scattering information. While the tritium and ^{3}He data comparison provides information regarding the rule of an extra proton or neutron in the nucleus of the simpler nuclei. By using heavier targets, which give higher rates, it is possible to study the A dependency (number of nucleons, protons and neutrons, in the target nuclei), e^- and $\mu^\pm$ scattering experiments have found some intriguing results that show the quarks in heavy nuclei are not simply confined to their protons or neutrons as some models have suggested. Testing this with high statistics neutrino scattering experiments is important. This data could also be used to compare with nuclear models that exist for N-N, π-N, e-N, γ-N and μ-N interactions; and even-

tually to formulate models of ν-N and $\bar{\nu}$-N interactions. With the ultimate goal of formulating a comprehensive theory that works for all interactions simultaneously.

τ *Neutrino:* With the high energy neutrino beam option of NuMI there is the possibility to do ν_τ detection from a point source which would further require a small emulsion active target, but due to particle rates it would have to be changed often. The physics prospects are higher statistics ν_τ detection, and short baseline neutrino oscillation. In this case the detector would be used to trigger on those events to search for in the emulsion. Due to the intense neutrino beams these emulsion targets should be highly segmented and easily changed. The multiple drawer system envisioned for the MINOS far detector is a possible choice [10]. If CP violation studies are ever to be done in the lepton sector, then the oscillation rate of $\bar{\nu}_\mu \rightarrow \bar{\nu}_\tau$ from disappearance will have to be compared to $\bar{\nu}_\tau \rightarrow \bar{\nu}_\mu$ from appearance, but it will be necessary to have a small emulsion experiment at the near site to determine the $\bar{\nu}_\tau$ initial intensity.

DETECTOR REQUIREMENTS

An experiment to look for strange particle production by neutrino interaction does not have to be very large, but does have several things it must perform well. A simple basic sketch of the conceptional detector design is shown in figure 1. There is the need for a veto array in front of the target and around the sides to
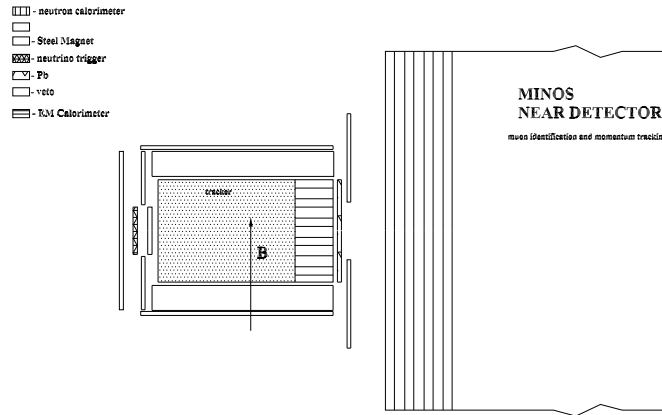
FIGURE 1. Conceptual design of a neutrino strange-particle production experiment.

catch any escaping particles, a target which could possible be: liquid, different materials or maybe even active. A tracking chamber in a magnetic field to be able to track and measure the momentum of all the charged particles, with the ability

to reconstruct the decay vertex of the neutral strange particles (Λ^0, Σ^0, K^0 ...). A good electromagnetic calorimeter, for electrons and especially photon pairs to be able to see $\pi^0 \to \gamma\gamma$. There is the need for the ability to distinguish protons, $\pi^{\pm}$, and $K^{\pm}$. Since the neutrino beam is not extremely high energy these particles will be relatively low in momentum. Permitting their identification by dE/dx in the tracking chamber or TOF. By having the experiment sit in front of the MINOS near detector, information from it can be used to identify muons and measure their charge and momentum. Also, the first 3-5 interaction lengths in the MINOS near detector can make a nice hadron calorimeter for identifying neutrons.

There are many advantages for both experiments to be located together. The cost effectiveness of producing the maximal physics from the NuMI neutrino beam is the most obvious. Each experiment can use information from the other to help calibrate. This experiment could measure more precisely the neutrino beam content and its radial distribution. Also protons and π^- from Λ^0 decay can be identified and then the response of the MINOS near detector studied so that hadron/muon identification in MINOS can be better understood as a function of momentum.

CONCLUSIONS

It is hoped that such an experiment can be organized in the next year with detailed detector designs, physics goals achievable and a sufficiently funded collaboration formed. Such an experiment can be of diverse interest to both the high energy and nuclear physics communities and represents an opportunity of cooperation. Furthermore, it will give another reason for the NuMI project to operate intense neutrino beams, which increase the physics yield from the neutrino flux that will be provided for the other experiment.

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