Possibilities for an off-axis near detector in the NuMI beam

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This paper describes a possible near-source detector for the Fermilab NuMI neutrino beam with the purpose of measuring neutrino interactions and NuMI beam fluxes in the few GeV energy range. Such an experiment would be an important supporting part of the program to probe neutrino mixing, masses and CP violation through the observation of $\overset{(-)}{\nu}_{\mu} \rightarrow \overset{(-)}{\nu}_{e}$ transitions in low energy conventional neutrino beams. It would also provide the opportunity to compare electron and neutrino-nucleon cross sections carefully at these energies and probe quark-hadron duality.

1. Introduction and goals

Neutrino cross section measurements in the 0.7-3.0 GeV range are of great current interest to the neutrino physics community. This is the optimal energy range for the beams of the planned next generation of accelerator-based neutrino experiments that will probe neutrino mixing, masses and CP violation through the observation of $\overset{(-)}{\nu}_{\mu} \rightarrow \overset{(-)}{\nu}_{e}$ transitions [2]-[4]. Precision cross section measurements in this energy range are also of interest to the nuclear physics community which strives to understand the nuclear dependence of neutrino and electron cross sections, nuclear medium effects on the final state and the nature of quark-hadron duality [5]-[9].

The proposed experiment, of interest to both the neutrino and nuclear communities, has a fully-active 2 ton (fiducial volume) target and tracking calorimeter. The goal is to create a detector that can detect and distinguish neutral-current (NC) and charged-current (CC) $\overset{(-)}{\nu}_{\mu}$ and $\overset{(-)}{\nu}_{e}$ interactions, and provide an energy measurement for the final state lepton in CC events. It is also designed to distinguish among the primary processes in this energy range, which are quasi-elastic scattering and inelastic charged and neutral pion production. The experimental proposal allows for the use of different target materials such as iron, carbon and water, which will yield data for detailed comparisons of electron and neutrino scattering on different nuclei and provide cross section information on target materials appropriate for envisioned long-baseline experiments. Through modular and flexible design, this detector can be modified to use materials and sampling fractions similar to that of a long-baseline far detector. This enables the detector to act as a near monitor and test-bench for the far detector in a long-baseline experiment.

2. Concept of the detector

The conceptual detector described here is preliminary. Optimization of size, segmentation versus costs, technology, etc. will be done with a full simulation at the time of a formal proposal. The parameters shown here are based on physics criteria and scaling arguments from existing detectors.

A schematic of the conceptual design is shown in Figure 1. It consists of an active target (Figure 2), followed by a sampling electromagnetic shower counter and a magnetized range detector. It is preceded by an upstream sampling iron scintillator target and an instrumented upstream ac-

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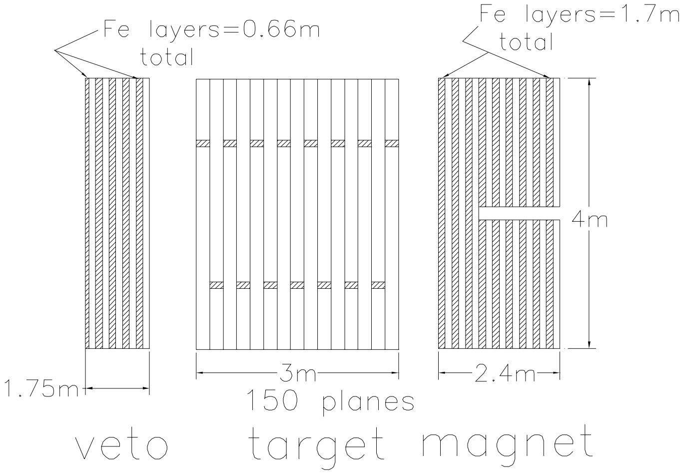

Figure 1. Conceptual layout of the components of the detector. A 4 m x 4 m active target, 3 m deep, is followed by a sampling calorimeter and magnetized range detector and preceded by an instrumented upstream veto.

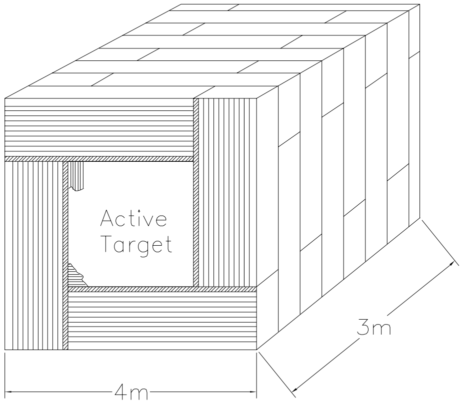

fig 2

Figure 2. The beam's view of the active target. In each plane, the inner 2×2 m section is solid scintillator strips; the outer 1 m on each side consists of mixed scintillator and steel bars as described in the text.

tive veto. A layout of individual components of one of the active-target detector planes are shown in Figure 3.

Good energy resolution, tracking, and identification of very short range particles like recoil protons, requires a fully active target such as scintillator. There is a natural preference for a low Z materials which give higher event rates for a given sampling in units of radiation lengths. The mass of target material is driven by the needed statistical precision. The target mass presented here was calculated to provide a number of electron-neutrino events sufficient to predict the background level in a far detector in a long-baseline experiment at a precision of approximately 5%, assuming the beam and detector location(s) described below.

The active scintillator target is $4 \times 4 \times 3$ m^3 with an inner fiducial volume of $1 \times 1 \times 1.9$ m^3. The depth of the target is driven, in part, by the desire to convert photons from π^0 decays.

The basic design element is 75 $\hat{x}$ and 75 $\hat{y}$ planes of 2×2 cm^2 strips of plastic scintillator, 4 m long. The strips are read out on one side with wavelength shifter fibers which are placed in grooves along each strip. Each plane contains 200 strips.

The target alone is insufficient to fully contain the muons, charged hadrons and electromagnetic showers created in the interactions. To make the target large enough for full containment is impractical. So, the fully-active target is supplemented with a denser range detector or a combined magnetized range detector/iron spectrometer downstream and at the sides. In the conceptual design, downstream of the target is a Fe-scintillator sampling electromagnetic calorimeter and a magnetized toroid iron scintillator range detector/muon spectrometer 4×4 m^2 in transverse dimension The total depth of the electromagnetic calorimeter and range detector is 1.7 meters of Fe. The first 20 Fe plates are 1 cm thick and serve as a 11.4 radiation length electromagnetic calorimeter. The remaining 1.5 m of Fe is magnetized and is sampled every 5 cm to contain and measure hadron energy and muon range. In this initial conceptual design the active material is similar to that in the active target, with alternating $\hat{x}$ and $\hat{y}$ samples. The range measurement is expected to yield a muon energy resolution of approximately 25 MeV. The entire electromagnetic calorimeter and magnetized range detector are shown in Fig-

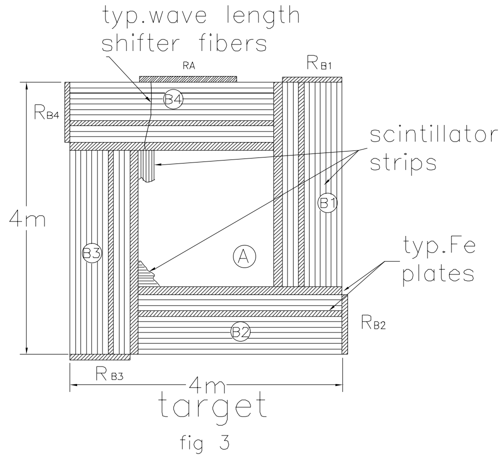

Figure 3. One plane of the active target.

ure 1 with a physical length of 2.4 m, including the sampling counters.

Upstream of the target is a 65 cm thick iron 4×4 m^2 Fe-scintillator target/veto. It consists of an initial 20 cm passive iron shield, followed by five 1 cm planes with active scintillator strip planes as in the active target. The fiducial volume of this target/veto in its use for studying neutrino cross-sections on iron would be $0.4 \times 2 \times 2$ m^3 or 12.8 tons. The total length is 1.75 m, including the active material. Another option for the active portion of this veto would be to replace it with material from a long-baseline far detector if the absorber there is not carbon.

To reduce the transverse detector dimensions and still provide containment, the transverse edges of the detector surrounding the target are formed from sections of steel absorber and scintillator as illustrated in Figures 2 and 3. The inner 2×2 m^2 area in this concept is solid scintillator (region A in Figure 3). Four identical scintillator/steel absorber sections are shown as regions B1-B4, completing a 1 m thick "picture frame" around the fully active inner region. The inner 20 strips (40 cm total) of the 1 m thick "picture frame" are configured to make an electromagnetic calorimeter by alternating between 2 cm thick iron strips and 2 cm thick scintillator strips. The outer 30 strips (60 cm total) are configured as a muon range detector and would be constructed of 5 units, each with 5 iron strips followed by a single scintillator bar.

The counter planes are all read on one side from the regions marked with "R" in Figure 3. An advantage of the above design is that all the planes are constructed in the same way. When placed in the target, the planes are rotated by successive 90 degrees to form a pattern of x, y, x, y planes which are read out on alternate sides.

This design is flexible and allows sections of the inner part of this active detector to be replaced with any type of target material (active or passive). The design can be modified to include RPC readout and/or a water/scintillator target in order to mimic and make measurements of direct relevance for a far detector [2][3].

3. Beam and location

It is proposed the detector be placed off-axis in the existing NuMI neutrino beam at Fermilab. Initially, it will run parasitically with the MINOS experiment using the Low Energy (LE) beam configuration[10].

The choice of going off-axis is due to the monochromatic nature of the neutrino beam off-axis. The kinematics of off-axis beams is such that charged pions of all energies decay to neutrinos of approximately equal energies at a fixed angle off-axis.

For short-baseline experiments, a narrow band beam, particularly one that varies in a predictable way as a function of angle from the source, is valuable for measuring neutrino cross-sections, since incoming neutrino spectrum is well-known. This allows relative reaction rates to be measured as a function of energy in a straightforward manner.

In long-baseline oscillation experiments, a narrow band beam can be chosen to produce maximal oscillation probabilities because neutrino appearance and disappearance probabilities are functions of L/E only. Another important feature for massive detectors with difficulty in separating neutral-current (NC) interactions of muon neutrinos from charged-current (CC) reactions of other flavors of neutrinos is the ability to use visible energy as a discriminant. For CC events, the total neutrino energy is observed in the detector, but for NC events, the unobserved final state neutrino can carry off significant energy. Therefore, high energy NC events appear as oscillation candidates at lower energy. A monochromatic beam minimizes this "feed-down" background from NC interactions.

The proposed near detector would to be located in a new experimental area in the access tunnel to the present MINOS on-axis near detector, about 880 meters from the production target, shown in Figures 4 and 5. Three sites are being investigated that would require no new excavation. One is in the MINOS near hall access tunnel. A second is just upstream of the vertical shaft leading to the MINOS hall. The third is in the access tunnel near the absorber, upstream of the muon alcoves.

The three potential sites pose different utility, maintenance and operations issues. Also, they cover a range of angles with respect to the NuMI beamline axis, which means the neutrino spectrum varies from position to position. This can be advantageous, as the peak neutrino energy can be changed by moving the detector. For example, a 23 mrad angle gives a peak neutrino energy of 1 GeV, while an 11 mrad (similar to that of the proposed off-axis long-baseline far detector [2]) angle would give a peak energy of 2 GeV.

3.1. Neutrino Fluxes

Figure 6 shows the relative number of ν_μ neutrino charged-current events induced in the detector as a function of ν_μ energy for the NuMI low energy (upper plot) and medium energy (lower plot) beams for on-axis and several off-axis configurations. The overall neutrino flux drops as the distance off-axis increases. However, the beam becomes more collimated in energy (narrow-band) and the high energy tail is reduced. The reduction in this high energy tail is critical in a long-baseline experiment where neutral-current interactions from the high energy tail can mimic ν_e charged-current events.

Relative to the flux in the proposed far off-axis detector, the flux in the near off-axis detector is wider because the neutrino source is not point-like at short baselines, but the peak energies and electron neutrino backgrounds are very similar. In addition, the flux in the off-axis detector is more similar to that in the proposed far off-axis detector than that in the proposed on-axis near detector [11]. This is very important given the mission of the near detector in a long-baseline experiment.

3.2. Comparison to the other off axis effort

Currently, two $\nu_\mu \rightarrow \nu_e$ 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 [3], 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 [2]. This beam would have a peak energy of 2 GeV, thus making possible the observation of matter effects. Another intriguing possibility for this experiment is to move further off-axis to a lower energy to run at the second maximum of the oscillation pattern where sensitivity to CP violating effects is enhanced. Both experiments have potential upgrade paths to more intense proton 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.

4. Conclusions

A fully-active detector positioned near-source, slightly off-axis from the NuMI neutrino beam at Fermilab would be ideal for measuring neutrino cross sections and NuMI beam fluxes in the few GeV range. The cross section information, taken on different nuclear targets, is critical for the next major steps in the program to probe neutrino mixing, masses and CP violation. In addition, the comparison of neutrino scattering

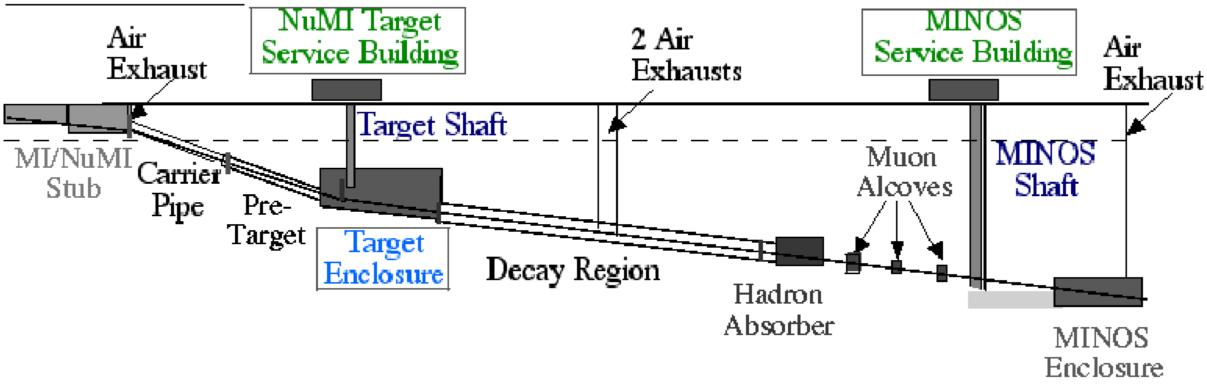

Figure 4. Access tunnel between the NuMI near detector hall and shaft. A new experimental hall located to the west of this tunnel would provide the correct location for the proposed new off-axis near detector.

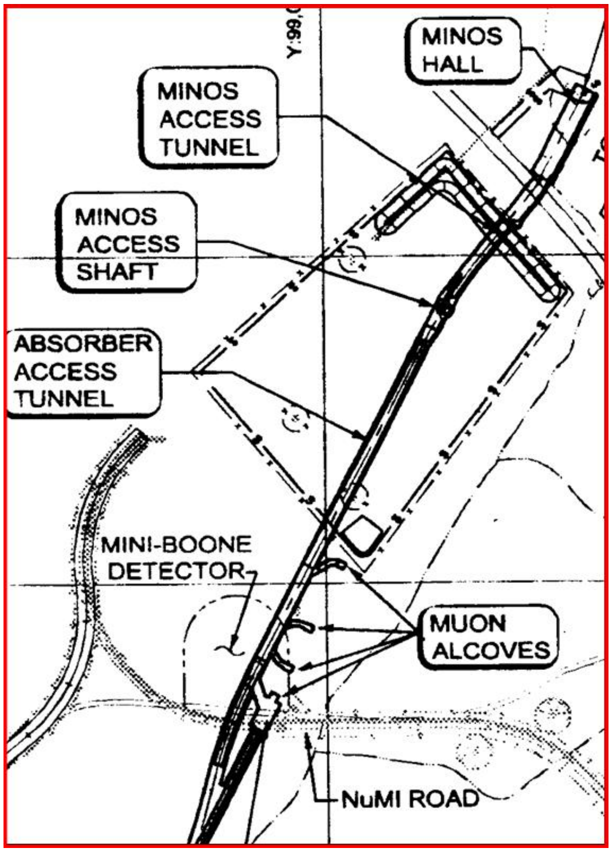

Figure 5. Overhead view of access tunnel layout.

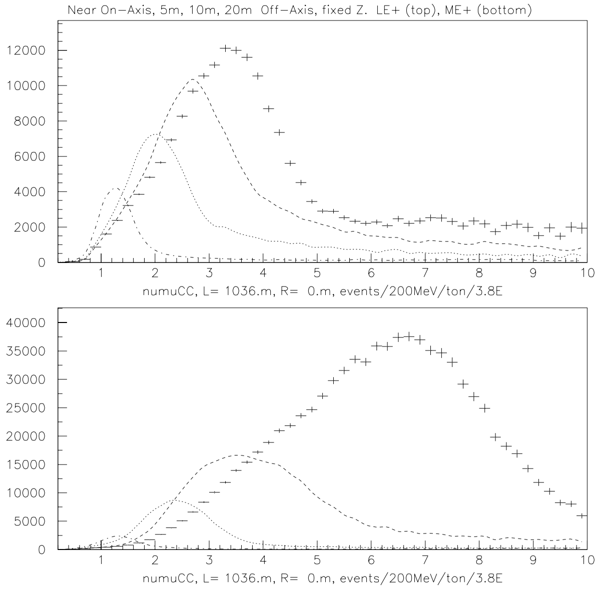

Figure 6. Relative event rate from the on and off-axis neutrino beams for the NuMI low energy (upper plot) and medium energy (lower plot) beams. The crosses correspond to the on-axis ν_μ neutrino-induced CC events, while the curves toward the left of the on-axis curve correspond to the event rates in detectors successively 5, 10, and 20 meters off axis, respectively.

with electron scattering on the different nuclear targets can provide data to probe the nuclear dependence of such cross sections and quark-hadron duality. Such a detector might also serve as a test facility and a flux monitor for the planned NuMI off-axis far-detector in the long-baseline experiment under discussion.

The proposed design is highly modular, consisting of a 2-ton solid scintillator target (fiducial region) with an upstream iron/scintillator target/veto and a downstream magnetized range detector and iron spectrometer. The fully-active fiducial volume is surrounded on the sides by a iron/scintillator shell. The modular design allows for insertion of different types of target materials and detector sections that mimic the planned NuMI far-detector.

The advantage of the off-axis NuMI neutrino beam is that the spectrum is collimated in energy. The energy of the peak flux can be chosen by varying the angle off-axis. In addition, the near off-axis flux is similar to that which will be seen by the far off-axis detector.

Several off-axis sites in the NuMI/MINOS access tunnels are under investigation. It appears that no additional excavation will be necessary to support the proposed experiment.

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