Proposal for Detector R&D for an Off Axis Detector Using the Fermilab NuMI Beamline

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Introduction

Proposal Overview

We are proposing a program of R&D as an initial step towards eventual construction of a large detector, located at about 10km off the NuMI beam line, about 800 km from Fermilab. This detector will be optimized for the study of $\nu_\mu \rightarrow \nu_e$ oscillations in the E/L range where this transition would most likely be dominated by θ_{13}, the as yet unmeasured third mixing angle in the MNS matrix. Significantly improved sensitivity compared to the MINOS experiment will be possible due to the following key features:

1. A detector with roughly 10 times more total mass but also with improved ability to identify ν_e CC events from NC backgrounds.
2. A lower energy beam with a narrower energy distribution which will be made possible by placing the new detector off axis.
3. An increased intensity of low energy neutrinos which comes both from the off axis location and an increase in the number of protons which can be delivered to the NuMI target.

We visualize a three year long effort of detector development before one would have sufficient understanding to be able to start construction of the full scale detector. The focus of activities during each year will be:

a) first year – basic R&D on detector technologies which will allow us to converge on the optimum one by January 2005 (assuming funding at the level and timing in this proposal). Currently, liquid scintillator technology is the baseline with glass RPC's the other alternative being considered. The activities will involve studies of basic detector construction issues, possible beam tests, simulations, studies of large structure engineering, and investigations of possible on the surface location issues. We note that the area of detector construction is more than 10 times that of the scintillator for MINOS. Hence the detector studies are aimed at addressing both basic performance issues but also performance versus cost considerations. We will also undertake construction of a small surface detector to assure that cosmic-ray induced backgrounds are as negligible (as anticipated).
b) second year – further optimization leading to finalization of the design for the technology chosen and subsequent engineering design. We envisage initiation of construction of a small scale detector (Near Detector for eventual experiment) with the chosen design towards the end of that year.
c) third year – construction of the Near Detector, and its installation in the MINOS Hall at Fermilab. Initiation of data taking in the NuMI beamline with the goal of obtaining valuable new data on neutrino interactions in the few GeV range.

The nature of the proposed work is such that we are able to present detailed description of work, budget, and responsibilities only for the first year. The situation for the subsequent two years will be clarified once the final technology decision is made. However, we do present some picture of the anticipated work in the latter two years.

Approximately 30 institutions have thus far joined in work on planning the Off Axis Experiment. For this proposal, we list only those institutions which plan to undertake substantial new efforts on detector R&D for this experiment which will require additional funding beyond their regular grants. Although Fermilab requests no support from this proposal, they are a key collaborator in this effort and we explicitly list them and their connection to activities in this proposal. We do not list any foreign collaborators here although some are contributing. A separate overall experiment proposal is in preparation for submission to the Fermilab PAC which will include a broader range of proponents than are listed in this R&D proposal.

Neutrino Oscillations

Recently the SuperKamiokande, K2K and Soudan 2 experiments have provided very strong evidence that the muon neutrino undergoes flavor changing transitions. These transitions are seen for neutrinos whose path length divided by energy (L/E) is of order ~500 km/GeV. SuperKamiokande also has some supporting evidence that these muon neutrinos are transformed primarily into tau neutrinos. Although the SuperKamiokande detector has some sensitivity to flavor transitions of electron neutrinos, their data provides no evidence that electron neutrinos are involved in these transitions. In fact, the Chooz reactor experiment provides a tighter constraint on the upper limit on the probability of electron neutrino flavor transitions of order 5-10%, at the values of L/E for which SuperKamiokande sees muon neutrino flavor transitions. This leaves open the interesting and important question: What is the role of the electron neutrino in flavor transitions at these values of L/E? A measurement or stringent limit on the probability of $\nu_\mu \rightarrow \nu_e$ for values of L/E ~500 km/GeV is an important step in understand these neutrino flavor transitions in atmospheric neutrinos. As the NuMI beam is primarily a ν_μ beam, the observation of ν_e appearance would address this question directly. This measurement is the primary goal of the experiment described by this proposal.

The SNO experiment has recently reported large transitions of solar electron neutrinos to muon and/or tau neutrinos both with and without salt added to the heavy water. SuperKamiokande studying solar neutrinos and KamLAND studying reactor neutrinos also see large electron neutrino flavor transitions. From a combined analysis, the L/E for these flavor transitions is a factor of ~30 times larger than the L/E for flavor transitions in atmospheric muon neutrinos. These transitions occur for an L/E such that the transition probability $\nu_\mu \rightarrow \nu_e$ measured by an experiment in the NuMI beam will also have some sensitivity to the flavor transitions associated with solar neutrinos through interference effects.
The LSND experiment has reported small muon anti-neutrino to electron anti-neutrino transitions for values of L/E which are less than two orders of magnitude smaller than the transitions seen in atmospheric neutrinos. However this transition probability is very small, on the order of 0.3% of the one observed for atmospheric and solar neutrinos. If this result is confirmed by the up coming mini-Boone experiment, this transition could be an important background for a measurement of $\nu_\mu \rightarrow \nu_e$ transitions at the larger values of L/E associated with atmospheric neutrinos.

Extensions to the Standard Model are required to explain the phenomena described here. The simplest and most widely accepted extension is to allow the neutrinos to have masses and mixings such that these phenomena are explained by neutrino oscillations. The masses and mixing of the neutrinos in these extensions would be the low energy remnant of some yet to be determined high energy physics. Thus, neutrino masses and mixing provide a unique window on physics that is inaccessible to current or near future collider experiments. One popular theory is the so called “seesaw” scenario where the active left handed neutrinos seesaw off their heavier right handed (sterile) partners leaving three very light Majorana neutrinos. It is already clear that the masses and mixings in the neutrino sector are very different than the masses and mixing in the quark sector and that a detailed understanding of the neutrino masses and mixings will be important in differentiating fermion mass theories. Also, they may provide the key to advancing our theoretical understanding of this fundamental question.

If the neutrinos have masses and mixings then the neutrino mass eigenstates, $\nu_i = (\nu_1, \nu_2, \nu_3, \ldots)$ with masses $m_i = (m_1, m_2, m_3, \ldots)$ are related to the flavor eigenstates $\nu_\alpha = (\nu_e, \nu_\mu, \nu_\tau, \ldots)$ by the equation

$$|\nu_\alpha\rangle = \sum_i U_{\alpha i} |\nu_i\rangle \qquad (1)$$

The charged weak current, for the neutrino flavor states, is given by $J_\lambda = \overline{\nu}_L \gamma_\lambda \ell_L$, where $\ell = (e, \mu, \tau)$ is the vector of charged lepton mass eigenstates. In the absence of light sterile neutrinos, the 3 × 3 lepton mixing matrix U is unitary. Lepton flavor mixing was first discussed (for the 2 × 2 case) by Maki, Nakagawa, and Sakata.

If we restrict the light neutrino sector to the three known active flavors and set aside the LSND results, then the unitary matrix MNS matrix, U, can be written as

$$U = \begin{pmatrix} c_{13}c_{12} & c_{13}s_{12} & s_{13}e^{-i\delta} \\ -c_{23}s_{12} - s_{13}s_{23}c_{12}e^{i\delta} & c_{23}c_{12} - s_{13}s_{23}s_{12}e^{i\delta} & c_{13}s_{23} \\ s_{23}s_{12} - s_{13}c_{23}c_{12}e^{i\delta} & -s_{23}c_{12} - s_{13}c_{23}s_{12}e^{i\delta} & c_{13}c_{23} \end{pmatrix} \qquad (2)$$

where $c_{jk} \equiv \cos\theta_{jk}$ and $s_{jk} \equiv \sin\theta_{jk}$.

With this labeling, the atmospheric neutrinos oscillations are primarily determined by θ_{23} and Δm^2_{32}, whereas the solar neutrino oscillations depend on θ_{12} and Δm^2_{12}, where $\Delta m^2_{ij} = m_1^2 - m_j^2$.
From SuperKamiokande we already have some knowledge of $|\Delta m^2_{32}| = (1.5 - 3.5) \times 10^{-3}$ $(\mathrm{eV})^2$ and $0.35 < \sin^2\theta_{23} < 0.65$ (*i.e.*, $\sin^2\theta_{23} > 0.91$). Note the substantial uncertainty in these atmospheric measurements. In contrast, the combined analysis of the SNO, SK and KamLAND experiments gives $\Delta m^2_{21} = +7.1 \pm 2.0 \times 10^{-5}$ eV^2 and $\sin^2\theta_{12} = 0.5$ excluded at more than 5σ. This corresponds to $0.71 < \sin^2 2\theta_{12} < 0.91$. For the purposes of this experiment our knowledge of the solar parameters is already in good shape and is expected to improve with time.

Chooz (and SuperK) provide us with a limit on $\sin^2(2\theta_{13}) < 0.18$. The Chooz limit is dependent on the input value used for $|\Delta m^2_{atm}|$; for the current central value 2.5 $\times 10^{-3}$ eV, this limit is $\sin^2(2\theta_{13}) < 0.11$, while for $|\Delta m^2_{atm}| = 2.0 \times 10^{-3}$ ev^2, it is $\sin^2(2\theta_{13}) < 0.18$ [4]. Thus, the proposed long-baseline neutrino oscillation experiment to search for $\nu_\mu \to \nu_e$ will be able to search over a substantial range below this upper bound.

The MINOS experiment [10] will provide a 10% measurement of the atmospheric Δm^2_{32} but not improve our knowledge of θ_{23}.This experiment has sensitivity to $\sin^2(2\theta_{13})$ only about a factor of two below the Chooz bound. Any future reactor experiment to measure $\sin^2(2\theta_{13})$ could improve our knowledge of this important parameter but such an experiment has no sensitivity to θ_{23}, the sign of Δm^2_{32} or the CP violating phase δ. Therefore, such a reactor experiment is truely complimentary to long-baseline experiment to observe $\nu_\mu \to \nu_e$.

For the normal hierarchy, matter effects enhance (suppress) the transition probability for neutrinos (anti-neutrinos) and vice versa for the inverted hierarchy. For a 2 GeV neutrino energy, matter effects give a 30% enhancement or suppression in the transition probability.

In summary the important measurements that could be made by the proposed experiment are

• Observation of $\nu_\mu \to \nu_e$ at an L/E in the range of 10^2 to 10^3 km/GeV, which would determine the ν_e role in atmospheric neutrino flavor transitions. In the neutrino oscillation scenario this is a measure of $\sin^2(2\theta_{13})$.

• Matter effects can be used to distinguish the two mass hierarchies and therefore determine the sign of Δm^2_{32}.

• For the Large Mixing Angle solution to the solar neutrino puzzle there is sensitivity to the CP violating phase in the channel $\nu_\mu \to \nu_e$.

• Precision measurements in $\nu_\mu \to \nu_\mu$ channel can measure how close θ_{23} is to $\pi/4$, that is maximal mixing. A comparison of $\nu_\mu \to \nu_\mu$ to $\overline{\nu}_\mu \to \overline{\nu}_\mu$ is a sensitive test of CPT violation since matter effects are suppressed in this channel.

Thus, there is a very rich neutrino physics program to be explored in a ν_e appearance experiment using the NuMI beam. Details of experimental and beam possibilities will be explored in subsequent sections.

Overview of the Experiment

The offaxis experiment can be described as having three major components: the neutrino beam, the near detector, and the far detector. We briefly describe here the most salient features of each.

Neutrino beam

The NuMI neutrino beam is currently under construction with scheduled completion at the end of 2004. The neutrinos originate from a 120 GeV Main Injector extracted proton beam aimed in the direction of the Soudan Laboratory. The protons strike the NuMI target where secondary pions and kaons are produced. These are focused by a two magnetic horn system and allowed to propagate and decay in a 675 m long decay pipe. The MINOS near detector hall is located 250 m downstream of the absorber which terminates the decay pipe. This hall will contain the MINOS 1 kt magnetized iron/scintillator near detector and will have room upstream of that where other detectors could be located. A feature of the NuMI neutrino beam is the ability to change the focusing optics configuration and hence the neutrino energy band accepted. Specifically, one accomplishes this by changing the relative position of the target and the horn and the separation between two horns. Whereas the movement of the second horn is complex logistically, the target position can be varied remotely (and therefore quickly).

The NuMI beam facility has been designed for the nominal proton intensity of 4 x 10^{13} protons on target per pulse every 1.9 sec – roughly 0.4 MW of beam power. The current goal for the initial proton intensity for the start of MINOS running is 2.5 x 10^{13}. In our simulations discussed below we have assumed the more optimistic design figure. Fermilab is undertaking an effort to raise the proton intensity over a several year period but a specific plan has not yet been instituted. The study of ν_μ->ν_e oscillations will be optimized if the beam is relatively monochromatic and flux at other energies minimized, so as to maximize the signal to background ratio. In addition, one wants to minimize background from τ->e decays so neutrino energy below τ production threshold is helpful. These conditions are realized in a NuMI offaxis beam.

At laboratory angles corresponding roughly to 90^o center of mass decay for the center of the accepted pion energy band, the energy of the emitted neutrinos is reasonably monoenergetic and depends only on the laboratory angle Thus in contrast with the 0^o beam, where neutrino energy is linearly related to the pion energy, a wide pion energy band contributes to a single neutrino energy resulting in a higher flux at that energy and significant depletion of the flux at other energies.
For the proposed beam, we plan to site the detector at about 15mr, where the neutrino energy is around 2 GeV. The flux is not too sensitive to the details of the focusing optics, a configuration close to medium energy NuMI tune appears optimum. The low energy tune, planned for the initial MINOS configuration, does not compromise the off axis flux very much.

Far Detector

We plan to construct a 50kt detector, with 1/3 radiation length longitudinal granularity, 3.5 – 5 cm transverse granularity, and a low Z material (wood product) as the inert material. Such a detector will allow sufficient e/μ discrimination and good e/π^0 separation. With this detector both ν_μ CC and all NC events can be suppressed to a level well below the level of the intrinsic ν_e component in the beam, while keeping the ν_e efficiency relatively high. Furthermore, the energy resolution of such a detector is good enough to reject most of the beam ν_e background which has a much broader energy distribution. The detector will be located on the surface. Rough calculations indicate that cosmic rays should not create appreciable background because of good rejection of those events obtained from low duty cycle (11 μs extraction time every 2 s), directional information, and relatively high neutrino energy. It is planned to verify this hypothesis experimentally by construction of a small detector using the proposed design which can quickly accumulate adequate data to test the hypothesis on cosmic-ray backgrounds (this is possible due to the fact that the ultimate large detector will have a duty factor of about 10^{-5} for neutrino beam data collection.

The baseline detector is based on liquid scintillator in segmented plastic extrusions and uses wavelength shifting fibers to transport the light and APD's as the readout. The individual cells are 3.75 x 3 cm in transverse dimensions and 15 m long. A "double" 0.8 mm wavelength shifting fiber will be placed in each tube by folding a single fiber back on itself at the end of each cell. Both ends of the fiber are routed to the same APD pixel. Peltier cooling will be used to reduce the intrinsic APD noise. The overall dimensions of the whole detector are 30 m (wide) by 15 m (high) and 162 m (long). The location of the detector will be either in northern Minnesota or southern Canada, 800-850 km away from the source. A potential advantage of the scintillation detector is the use of pulse-height information in event identification. The liquid scintillator technology also appears, given what we currently know, to be the cheapest option for construction of this very large detector.

The other technology being considered are glass RPC's, very similar to the design used successfully in the BELLE experiment at KEK. The proposed design calls for double layer RPC's, like in BELLE, of 2.84 x 2.42 m dimensions. They are packaged away from the site in 8.5 x 2.4 x 2.6 m containers containing 36 RPC's. The whole container package could be tested at the RPC production site and then transported to the far site. The RPC-based detector offers the possibility of two spatial dimensions of readout for every detector plane location. However, the signals from these detectors will probably only offer binary information for the pattern recognition characteristics of interest here. An interesting issue of R&D is to better understand the trade-offs in physics sensitivity in these two detector technologies in addition to questions of detector operation and cost of construction.

Near Detector

The near detector for the offaxis experiment will have a double function: to predict the background levels at the far detector and to study neutrino interactions in the few GeV region. The rates at the near site will be about a million times higher per unit mass of the detector (roughly the ratio of distances squared). Thus the mass can be about a thousand times lower than that of the far detector (~50 tons) and still obtain a reasonably large number of events.

The MINOS near detector will provide some important information on the issues relevant to the offaxis experiment, most importantly information on the neutrino spectrum (from the observed ν_μ CC events) which can be used to estimate reliably the beam ν_e background. Nevertheless, we think it is important to also have a detector employing the same technology as the far detector to make a more direct estimate and to have better resolution to study individual neutrino interaction channels. One issue is the optimum strategy of extracting the background estimate; an important consideration is the fact that the three principal backgrounds: beam ν_e, NC and ν_μ CC events do not extrapolate in the same way from a given near detector to the far site. A related issue is the pros and cons of an on-axis vs off-axis near detector. Locating it in the MINOS Hall would provide more space and thus more flexibility, but effectively provides only an on-axis beam. The alternative is an off-axis site in the side tunnel where the available space would probably restrict the near detector to transverse dimensions no more than 4m. That location, however, would allow positioning the near detector at the same angle with respect to the beam as the far detector.

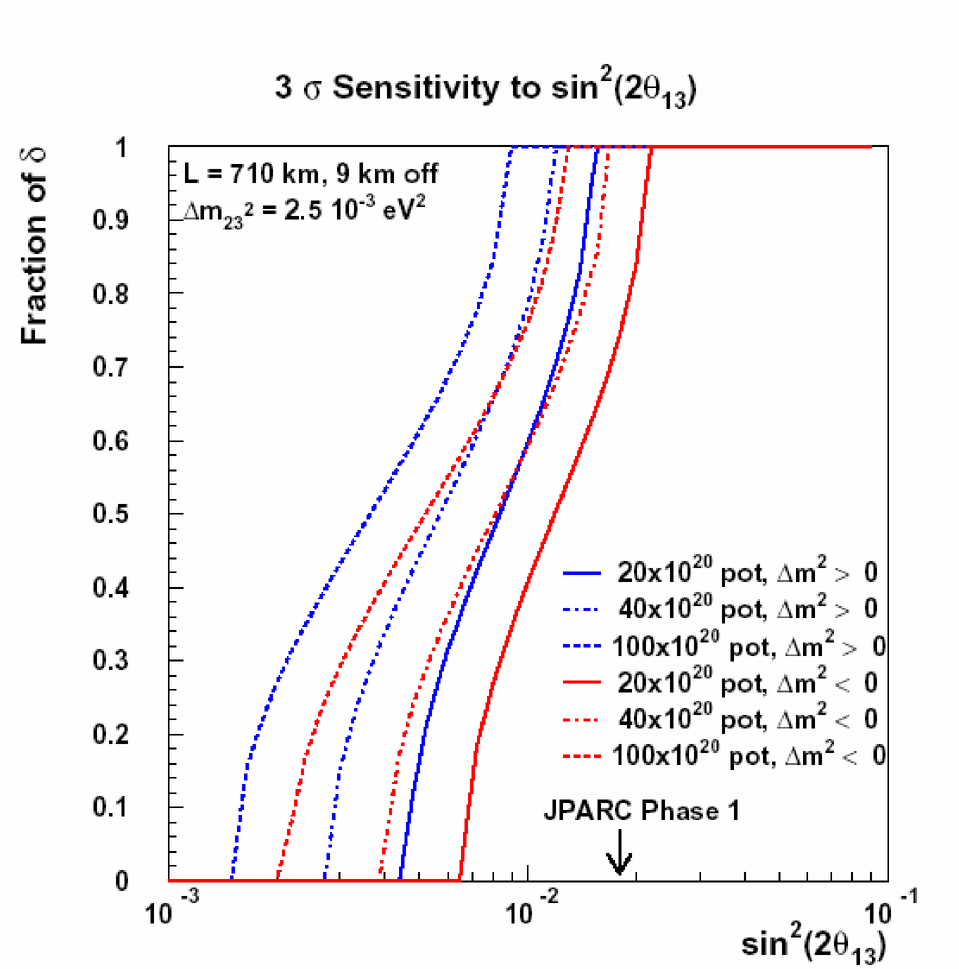
Physics Potential of the Off-Axis Experiment

Neutrino oscillation physics

The primary goal of the NuMI Off-Axis Experiment is the measurement of $\nu_\mu \rightarrow \nu_e$ oscillations with a sensitivity approximately an order of magnitude greater than that of the MINOS experiment. Figure 1 shows the calculated 3 standard-deviation discovery limits for $\nu_\mu \rightarrow \nu_e$ oscillations in terms of the three unknown parameters, $\sin^2(2\theta_{13})$, the sign of Δm_{13}^2, and the CP-violating phase δ, assuming that $\Delta m_{23}^2 = 0.0025$ (eV/c)^2. The vertical axis represents the fraction of possible δ values for which a 3-σ discovery could be made. In other words, 0 represents the limit for the most favorable value of δ for a given $\sin^2(2\theta_{13})$, 1 represents the least favorable value of δ, and 0.5 represents a typical value. The lines represent the two possible values of Δm_{13}^2 and different assumptions on the number of protons on target (pot) that the experiment might see in a five year run. (If the figure is being viewed in gray scale, the line to the right for each number of protons represents the inverted mass hierarchy.) 20×10^{20} pot represents a reasonable estimate of what Fermilab might be able to deliver in the time frame of the experiment with incremental Booster and Main Injector improvements, while 40×10^{20} pot is probably an upper limit to what could be achieved with incremental improvements. 100×10^{20} pot represents the expectation with the Booster replaced by a new Proton Driver[1]. The 3-σ sensitivity of the JPARC Phase I proposal is also shown. It is calculated for a somewhat higher atmospheric mass splitting, $\Delta m_{23}^2 = 0.003$ (eV/c)^2.[2]
A major long-term goal of the study of neutrino oscillations is the determination of all of the parameters of the mixing matrix including the CP violating phase δ, which could be related to the hypothesis of leptogenesis.[3] In general, since there are three currently unknown parameters to be determined, in general, at least three independent measurements will be needed for a full determination. Examples of such measurements are neutrino and antineutrino runs at different baselines and/or on different oscillation maxima, and electron antineutrino disappearance experiments from reactors.[4] It should be emphasized that one parameter, the sign of Δm_{13}^2, can only be measured in a long baseline experiment through matter effects in the earth. This is a ±30% effect for an experiment with the NuMI baseline, but only a ±12% effect for the shorter JPARC baseline. Without a measurement of the sign of Δm_{13}^2, the CP-violating phase δ cannot be determined with any precision. Thus, the NuMI Off-Axis experiment will be a crucial component of a longer-term program of neutrino oscillations. Figure 2 shows an example of expected results for a NuMI Off-Axis experiment neutrino run of 80×10^{20} pot plus an antineutrino run of 40×10^{20} pot combined with a 2-year JPARC Phase II neutrino run. The assumed NuMI fluxes are those that could be obtained in a 6 year run with a new Fermilab proton driver. The input point $\sin^2(2\theta_{13}) = 0.05$, $\Delta m_{13}^2 >$

0, $\delta = \pi/2$ is well measured with the mass hierarchy resolved to better than the 95% confidence level. Neither experiment could resolve the mass hierarchy by itself.

Figure 1. Three standard-deviation discovery sensitivity for $\nu_\mu \rightarrow \nu_e$ for the off-axis experiment. See text.



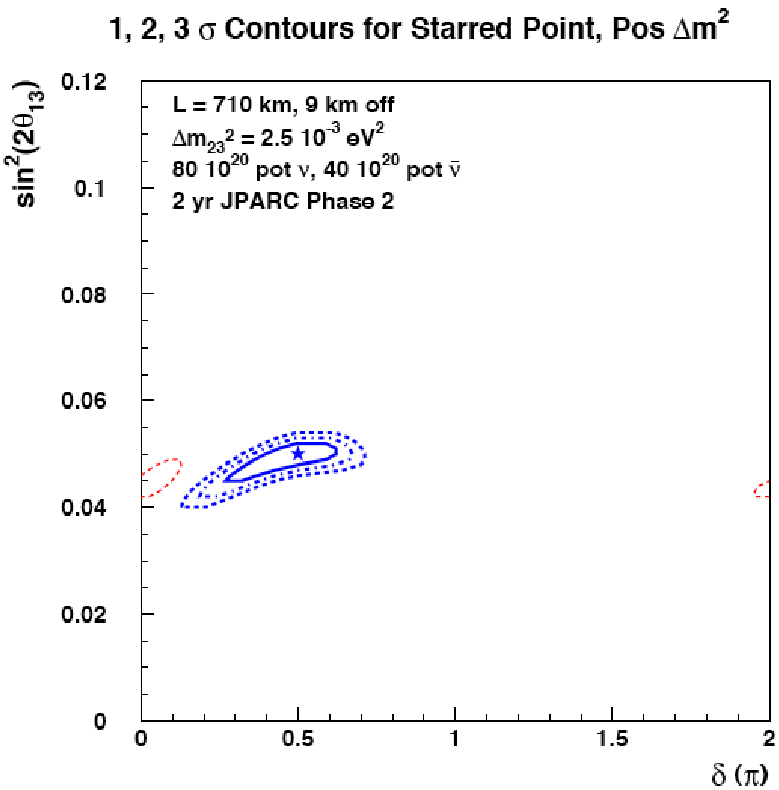


Figure 2: 1, 2, and 3 standard deviation contours for a NuMI Off-Axis neutrino run of 80×10^{20} pot plus an antineutrino run of 40×10^{20} pot combined with a 2-year JPARC Phase II neutrino run. The (red) dotted contour near $\delta = 0$ and 2π represents a 3 standard deviation contour for the wrong mass hierarchy.

Neutrino Scattering Physics

Although the primary purposes of the proposed near detector at NUMI are to serve as demonstration of concepts for a future NUMI off-axis detector and, ultimately, to provide input to the oscillation measurements in such a detector, there is also a broad menu of physics accessible at this detector. Unlike the MINOS near detector, the near detector proposed here will have very fine sampling and some sections that have a high fraction of active material. This leads to the possibility of clean measurements of exclusive final states, such as (quasi)elastic scattering and the production of exclusive baryon resonances in the final state.

The Q^2 distribution of elastic scattering is a subject of active interest in the nuclear physics community[5]. The identical measurement repeated in neutrino scattering offers the first opportunity for a precision probe of the axial nucleon form factors. At low Q^2, the region most important for oscillation measurements, these measurements measure the effective axial mass, m_A, and will allow for a comparison of this quantity against its measurement in pion electroproduction[6]. Also, the low Q^2 region is sensitive to Pauli suppression, and a detailed study of this region will allow for improvements in existing cross-section models[7] of this effect. Studies of this reaction at high Q^2, where there is little or no existing data, will allow for a test of the details of the axial form factor shape at high Q^2 where similar tests of the vector form factor in electron scattering have shown significant violations from the standard dipole form.

A second major topic of study with low energy exclusive neutrino reactions is the application of quark-hadron duality. Duality, which links low energy processes of discrete particle production to the DIS limit of scattering from quarks, has been extensively studied in charged-lepton scattering, and has been shown to hold in all unpolarized structure functions and even in nuclear dependence of cross-sections[8]. Studies in low energy neutrino interactions offer the chance to study duality in the axial current. Topics of particular interest include the understanding of the effect of isospin selection in the charged-current and tests of models of cross-sections in the resonance region[9]. The latter topic will ultimately lead to improved modeling of the low energy neutrino cross-sections important for oscillation experiments in the one to few GeV region.

Detectors

Scintillator Detector

We have selected liquid scintillator as the baseline technology for the active detector elements. To first approximation, the design is similar to that used for MINOS; alternate layers of scintillator and passive absorber. However, the larger scale of construction here makes use of liquid rather than solid scintillator more practical. Another important difference is that we propose to achieve both better quantum efficiency and lower cost by replacing the MINOS multi-anode photomultipliers with avalanche photodiodes (APD's). There are no fundamental detector technology issues to be addressed in this R&D. Rather, the work is designed to assure that the proposed construction techniques will work as planned and on the large scale as planned. The investigations that we propose should reveal cost savings from value engineering or, on the down side, additional hidden costs.

The design for the detector has three basic components: the absorber structure, the active detector modules and the photodetector with electronics. Although there is some interaction among these systems, to first order, each of these components can be modified separately in order to optimize their performance or minimize their cost without a major impact on the design of the other components.

The proposed absorber for the Off-Axis Detector is wood in the form of particleboard. Particleboard is an engineered wood product, which is low cost and produced in large quantities in the vicinity of the Minnesota end of the NuMI beam. In addition to its properties of low density and low Z, particleboard has sufficient structural strength to provide much of the required detector support structure. High efficiency, industrial strength fastening systems, such as quick-set, high-strength adhesives and cartridge-loaded screw guns, exist to install the fasteners required to assemble an particleboard structure. The overall Off-Axis Detector design thus incorporates the active scintillator modules into what is functionally a large monolithic block of wood.

Our plan for Off-Axis Detector construction is modeled on the successful MINOS experience. The lighter scintillator modules will be manufactured away from the detector laboratory and shipped to the site. They will be filled with liquid scintillator only after they are installed at the site. The massive quantities of particleboard will be produced locally from wood grown and harvested in the vicinity of the detector laboratory. The active elements and the particleboard will be combined on-site as the Off-Axis Detector is assembled. The geometry of the active detector elements is similar to that used in MINOS, but for the Off-Axis Detector, the scintillator strips will be nearly twice as long and are read out only at one end. To take advantage of standard particleboard tooling, the Off-Axis Detector will be sized in feet. The Detector cross-section will be 48 feet high by 96 feet wide. Forty eight foot long scintillator modules will be embedded into the particleboard structure and arranged to give alternate orthogonal views separated by about 1/3 of a radiation length of absorber. This Detector design and aspect ratio optimizes the fiducial volume of the detector with respect to both cost and ease of construction

The proposed photodetectors are avalanche photo-diodes (APD's) of the type used in the Compact Muon Solenoid (CMS) Detector at the Large Hadron Collider (LHC). They are commercially available in large quantities from Hamamatsu. One APD pixel will be used for each scintillator. APD's have a quantum efficiency several times higher than the photocathode in photomultiplier tubes (PMT's), hybrid photodiodes (HPD's) or image intensifiers (IIT's). The QE ratio can be as much as an order of magnitude for the wavelengths that are less attenuated by a long wavelength shifting fiber. Arrays of APD's are also significantly less expensive than PMT's or HPD's. However, APD's are low gain devices. We expect to operate the Off-Axis Detector at an APD gain of 100. This APD gain parameter requires a high gain electronic amplifier, integrated with the necessary shaping, timing, gating, and pulse height measuring circuitry. Such amplifiers have been developed and produced in quantity for silicon strip detectors. To reduce the thermal noise of the APD's, it will be necessary to cool them to approximately 0^{o}F using an electronic Peltier circuit mounted on each APD array. Calculations based on the measured performance of individual elements of the APD, electronics, and cooling systems show that a signal to noise ratio of about 5:1 is achievable for minimum ionizing particles at the far end of a scintillator strip. Measurements of the entire system noise using existing, but not optimized, electronics support these calculations.

The active detector modules will be based on those constructed for MINOS using wavelength shifting fiber to transmit the light produced in a long strip of scintillator. Using a plastic scintillator strip width and thickness of 4 cm x 1 cm yields a well documented performance for the extruded solid scintillator. Thicker cells (4 cm x 3cm) will reliably give at least the same performance for liquid scintillator at substantially lower cost. For MINOS construction, this cost differential was small but for the Off Axis experiment it is substantial. The light transmitted down the fiber from the far end will be increased in comparison with MINOS by having a single fiber make two passes through the scintillator with a loop at one end. This configuration helps to make single-ended fiber readout practical, reducing the number of readout channels, and yielding approximately four times as much light as would be observed from the far end of single, unmirrored fiber. Large quantities of liquid scintillator are currently used in KAMLAND and mineral oil in MiniBooNE. Large segmented plastic containers of liquid scintillator were used in MACRO for many years.

The major participants in the coordinated liquid scintillator R&D effort are: Argonne National Laboratory, Caltech, Fermilab, Harvard, Indiana, Minnesota, Rutherford Laboratory, Texas, Tufts, UCLA, and William & Mary. All of these groups have members with extensive experience with elements of the proposed technology. The effort will be coordinated by Minnesota and Caltech. Both Fermilab and Rutherford Laboratory are contributing significant engineering resources to this effort but request no funding from this proposal for the work on scintillator. Other engineering funds requested in this proposal are by Argonne Laboratory, Harvard, and Minnesota, all subsidized by other funding sources.

In addition to the important effort involved in this R&D, some major purchases of the material to be investigated are necessary. These include a die and small production run of the extruded plastic containers for liquid scintillator, small quantity custom electronic chip manufacture, and small quantity APD purchases. Smaller purchases include samples of various grades of mineral oil, several types of liquid scintillator, wavelength shifting fiber, glues, various grades of oriented strand board and particle board, specialized electronic test equipment for high gain low noise amplifiers, and commercial assembly equipment.

The goals of this effort in the first year will be:

1. Demonstrate adequate understanding of APD readout and electronics issues. Of special interest are the APD and electronics noise acting as a system and the integration with the necessary cooling for the low noise operation.
2. Demonstrate the reproducibility and stability of light output of the proposed scintillator modules.
3. Demonstrate system integration issues by constructing a prototype of a full plane of a liquid scintillator based off-axis detector with at least one fully instrumented prototype module capable of detecting cosmic ray events.
4. Verify the production cost model through engineering work on the large scale production.

The initial primary R&D responsibilities will be:

Overall coordination and integration of the project.

Minnesota and Caltech.

Scintillator module development.

Argonne – design of machines to manufacture liquid scintillator modules.
Caltech – aging and reactivity tests of components. Optimization of manufacturing procedures. Safety tests.
Minnesota – coordination of production and testing of modules. Extrusion production, component engineering, testing and development of quality assurance procedures. Computer simulations of detector performance to establish optimal geometry at minimal cost.
Indiana – large volume liquid scintillator handling including systems for delivery, mixing, and filling of modules. Extrusion assembly tests and reflectivity measurements.
Texas – Fabrication, design and testing of end manifold structures.
Tufts – determination of optimal liquid scintillator cell size and absorber thickness to enhance signal and reject background by developing computer models of low energy neutrino events.
UCLA – module component testing.

APD electronics and interfacing.

Fermilab – electronics design of low noise integrated circuit to process APD signal and its preliminary testing.
Harvard – control electronics for APD circuit including precise high voltage and temperature controls, triggering electronics, design consultation for integrated circuit. Testing of electronics with APDs.
Minnesota – coordination of APD electronics effort. APD interfacing to electronics. Testing of electronics with APDs. APD cooling and noise measurements.
Indiana – Acquisition and testing of APDs and electronics
Texas – Acquisition and testing of cooling devices and electronics, tests of APDs
Rutherford – APD interfacing to fibers, electronics packaging and cooling.

Large scale structure.

Argonne – Engineering of structure containing both absorber and scintillator modules. Large scale structural tests.
Fermilab – Engineering of structure containing both absorber and scintillator modules. Large scale structural tests. Safety analysis.
Minnesota – Design modifications of structure containing both absorber and scintillator modules. Installation design.
William & Mary – Coordination of large scale structure design and tests. Lifetime testing of absorber materials especially humidity and temperature variations. Safety tests.

RPC Detector

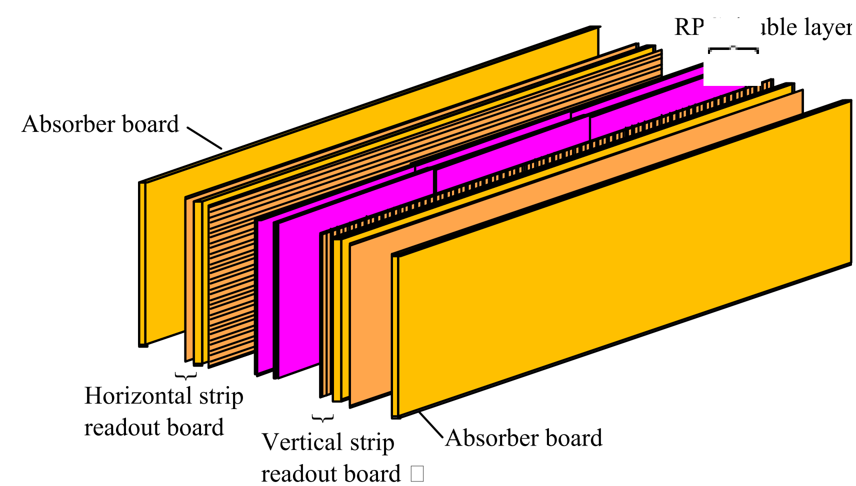


Figure 3 Exploded view of an RPC Readout Assembly

The alternate technology which we will pursue is glass Resistive Plate Chambers (RPC). This technology provides a good match to the scale of production for this experiment and has had a proven stable operation of a relatively large system in the Belle experiment. RPCs operate on a simple concept. A gas gap is formed between two plates of high bulk resistivity ($>10^{11}$ Ohm-cm) charged to high voltage. A charged particle crossing the gap initiates an electron avalanche that induces signals on nearby readout strips.[10]

A large body of practical experience with RPC technology has been accumulated over the last 10 years. Finding an appropriate resistive plate material for high rate environments (> 100 Hz/cm^2) has proven difficult. However, in the very low rate (<0.1 Hz/cm^2) conditions of a neutrino experiment, indications are that glass RPCs can operate indefinitely at their nominal efficiency.

Much that has been learned about building and operating glass RPCs comes from the experience of the Belle experiment[11]. In particular, their initial operation showed that the water content in the gas must be kept below 10 ppm. Subsequently, the Belle chambers with sizes ranging from 3.3 to 6.0 m^2 and covering a total area of ~2200 m^2, have operated in the streamer mode for over 5 years without a chamber failure or loss of efficiency. A number of Belle spares were obtained from Virginia Tech (builder of the Belle barrel chambers) and tested at Fermilab. No degradation in their performance was seen after sitting in a box for 5 years. One focus of the R&D program will be to develop low cost techniques for construction of the modules, RPCs, readout boards, and electronics, and to subject them to performance and accelerated aging tests where appropriate.

Absorber/RPC modules

A modular concept for an RPC based detector has been developed where unsampled energy depositions can occur in less than 1% of the volume.[12] Modularization simplifies the detector assembly at the experiment's remote site. Modules are constructed from 8' x 8' x 28' sheets of absorber (particleboard) strengthened by aluminum and steel in the critical corner post and end-plate areas. Secured to the end plates are 12 RPC/Readout board Assemblies (RRA) with integrated gas distribution, HV routing, and readout electronics. Each readout layer consists of two glass RPCs sandwiched between two views of readout strips which are layed onto the boards on the two sides of the gap for the RPCs (shown in Figure 3). On the module, services are bussed to each of the RRAs from just a few electrical and gas connectors. To keep the module weight below standard shipping limits, gaps are left between RRAs that are later filled with additional absorber sheets.

When a module arrives at the Northern Minnesota site, a relatively small crew adds 22 tons of absorber sheets to complete the 44-ton module. The module is then added to those previously stacked, ultimately forming layers two modules wide (56') and eight high (64'). Another crew attaches services and DAQ cabling and performs tests before another module is stacked on it. Stacking 2 modules per day, the 75 layers of the complete detector are stacked in less than 3 years.

RPC based detector R&D (Year 1)
The central goals of the R&D for the RPC based system in the first year will be to develop and demonstrate low cost production techniques and understand that these are acceptable for the performance stability of the glass RPCs. The university collaborators involved in this experiment are fortunate to have access to a pool of engineering expertise at the two national labs, Fermilab and Argonne.

i) RPC development (Fermilab, Michigan State, Virginia Tech, Chicago):
Using the Belle construction techniques a number of small RPCs will be built to investigate issues that affect the discrimination of electron showers from hadron or muon tracks. This will be followed by tests of different resistive coatings, glues, and gas mixtures, the latter to test the effects of various contaminants and recovery procedures. Although not requesting any funds in this proposal, a group from the Univ. of Chicago will also participate in some of this work.

A glass RPC operating in streamer mode has an intrinsic efficiency of about 95%. Two gas gaps are required to achieve efficiencies close to 100%. Belle used two independent chambers between the readouts. An RPC using three glass plates to form two gas gaps with common high voltage would lead to significant (>25%) reductions in RPC and HV supply costs, though higher applied voltages are required. Examples of such dual RPCs will be constructed and tested.

ii) Cosmic ray tests (Argonne, Fermilab, Virginia Tech):
Calculations indicate that an experiment on the surface without overburden will have no trouble rejecting cosmic ray backgrounds. Only extremely rare sources, such as neutrons interacting in the absorber have a remote possibility of being confused with electron neutrino CC interactions. Nevertheless, this prediction will be verified with a stack of 24 spare Belle chambers interleaved with particleboard absorber.

iii) HV supplies (Argonne):
Each RPC will have HV supplied with a current monitor to identify a problem chamber. A Cockroft-Walton supply has been designed and prototypes are being built for the cosmic ray test stand where they will be tested in an experiment type environment. Accelerated aging tests will also be performed. A current readout is integrated into the HV supply design and a readout system will be implemented for the test stand.

iv) Readout electronics (Fermilab, Argonne, Rochester)
With nearly 4 million channels, readout electronics for the RPC based detector will have to keep costs near $2.00/channel. RPC electronics are being developed at Argonne and Fermilab for a number of projects. Funding of this R&D proposal will accelerate the work on an ASIC for the Off-Axis experiment.

v) Module and RRA development (Argonne, Fermilab, Michigan State):
Two large particleboard laminates have been built to evaluate the structural properties of the material. A full scale mock up of a 12 RRA module will be constructed and subjected to mechanical tests to verify its integrity and ability to be stacked.

The horizontal and vertical readout strips are placed on sheets of particleboard absorber to maintain the density of the detector. Flexible fan-in circuits collect the signals from the strips and flat conductor cables transport signals on the back of the readout boards to the electronics. A second layer of particleboard stiffens the package and protects the cabling. A cost-effective procedure for production of readout boards, fan-in, and cabling will be identified, prototyped, and tested.

An RRA is constructed by mounting dual RPCs three across on the face of a horizontal readout board. A small region on the corner of each RPC is cut out to make gas connections between them and to pass bolts through the RRA package. The bolts secure the vertical readout boards to the horizontal readout boards over the RPCs. Gas lines and HV leads are routed on the top of the RRA to the module's outer edge. Electronics mounted at the outside edge of the RRA are connected to the readout board cables. The engineering to specify the details of the gas distribution, HV cabling, readout electronics mountings, and overall mechanical structure of the RRAs will be completed and a prototype built to test the efficacy of the design.

Selected technology based detector R&D (Years 2-3) *(All Institutions)*
A technology decision based on the preliminary results should occur at the end of the R&D program's first year. The R&D program for the 2nd year includes developing factory layouts, tooling, and quality control procedures, for production of the chosen technology. The collaboration expects to evaluate pre-production prototypes and a layer-0 at a laboratory site in the 3rd year.

Supporting Activities

Large Scale Engineering

Construction of a 50 kiloton detector will be a major undertaking and the cost of such a device mandates investigation into engineering methods aimed at reducing the cost of virtually every part and assembly. We recognize that the funding profile for such a project will necessarily extend over many years and that reducing the total cost can translate into a shorter path to data taking and physics.

The Liquid Scintillator scheme requires factories to insert looped wavelength shifting fiber into PVC multi-cell extrusions, to attach manifolds and optical connectors, to seal the whole module, and to test modules for fiber continuity and leaks. A deeper understanding of this large scale factory flow and development of automatic machines for some tasks should lead to reduced overall cost. The assembly of the Liquid Scintillator modules into a monolithic absorber of particle board at the final detector site may also allow automation not yet envisioned. Methods should be investigated to make the precision mixing and transfer of Liquid Scintillator from tankers to modules robust and leak free.

The Resistive Plate Chamber (RPC) scheme requires factories for RPC construction, for integration of RPCs into modules with 6 RPCs plus readout boards, and for Absorber frame and RPC integration. A deeper understanding of this large scale factory flow and development of automatic machines for some tasks should lead to reduced overall cost. In addition a complete understanding of the transportation model for moving partially assembled modules among factories could reduce the cost yet still retain a collaborating advantage of multiple construction sites at many institutions. The modular assembly of the RPC scheme may also allow absorbers other than particle board to be considered with potential for reduced cost. For example, where the material strength is not an overriding issue, replacing the particle board with gypsum drywall board or cellular foam concrete may be possible. Since RPCs require a specialty gas, there could be additional major automation and associated cost reductions available in the gas mixing plant.

The building to house a 50 kiloton detector also requires more investigation. We have preliminary designs for above ground buildings with no overburden and for slightly below ground buildings with a modest overburden, but the cost is large. Innovative building designs using stretched fabric over space frames or using air pressure supported domes should be looked at in more detail. Both these solutions typically require a smaller height to width ratio than our detector design, but perhaps some acceptable solution using intermodal shipping containers as the high walls can take advantage of these potentially cheaper structures.

Simulations

Significant work on simulations has already been done, the results of which convinced us that a Fermilab offaxis experiment in the NuMI beam has an excellent physics potential and allowed us to converge on liquid scintillator and RPC's as the two technologies that should provide optimum sensitivity for a fixed cost. Much work remains still to be done in this area, however.

The focus of the simulations work during the first year will be to provide information required for an informed definitive decision on the technology to be used. This will involve understanding the relative importance of two dimensional readout vs pulse height, the main distinguishing characteristics between scintillator and RPC's. Another important issue to resolve is the relative vulnerability to potentially different features and magnitude of various neutrino cross sections in the few GeV range (than we are assuming in simulations) which are not known well today.

The main task of the simulations during the second year will be to provide information required for making detailed decisions about the detector design, like transverse and longitudinal granularities. In addition, simulations are required to understand the requirements on the parameters of the Near Detector and its optimum location.

In the third year we see our software efforts shifting from simulations to developing analysis codes for the data to be taken in the Near Detector. We envisage that the code will be based on the MINOS system but significant additional work will need to be done.

Outreach Program

While it may seem unusual for an outreach program to have a development phase, the particular features of an experiment with a directed beam of particles aimed at a rural location call for such efforts in addition to materials aimed at more general audiences. Before the construction of the Soudan 2 nucleon decay detector (in the mid-1980's), the University of Minnesota began a series of town meetings in Tower and Soudan, where the laboratory was to be located, to explain what these "crazy but harmless" scientists were contemplating. The results of these meetings were entirely positive. The local community has been continuously interested and involved in the research program at the laboratory. These activities were duplicated by the MINOS collaboration during the construction phases of that experiment: several evening town meetings (in nearby Ely) were successful from both an educational and public relations perspective.

The first stage consists of the development of graphic materials that explain the basic features of an off-axis neutrino experiment. The most important topic to be covered is that the extreme size (and mass) of the detector is required because neutrinos are so elusive. The materials are to be developed with the assistance of Fermilab, and may be made available on CD's or DVD's. Large posters suitable for presentations at meetings would be useful, as would the development of computer-aided materials and handout brochures. These materials would first be available to the public (and local area residents) during the annual open house at the Soudan Underground Laboratory and during the summer State Park tours of the laboratory. The materials would be duplicated for utilization in the outreach activities of the various collaborating institutions.

When a site for the far off-axis detector is chosen, these materials will be used in a series of public meetings in the nearby communities. These meetings will serve as forums leading to the involvement of local schools and other community groups to further act as educational outlets. Involvement of the resident population of Native Americans will be especially encouraged.

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