

SciNOvA: A Measurement of Neutrino-Nucleus Scattering in a Narrow-Band Beam

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Abstract

We propose to re-instrument the existing scintillator from the SciBar detector used previously by the SciBooNE experiment and deploy the detector in front of the NOvA near detector where it will be exposed to the 2 GeV NuMI narrow-band beam. A fine-grained detector located in this narrow-band beam can make unique contributions to the measurement of quasi-elastic scattering, neutral-current elastic scattering, neutral-current π^0 production, and enhance the NOvA measurements of electron neutrino appearance and muon neutrino disappearance.

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1 Introduction

There now exists a unique window of opportunity to investigate the science of neutrino-nucleus interactions using an existing detector and neutrino beam at Fermilab. These measurements would complement recent and near-future measurements made by detectors in other neutrino beams, eg. MiniBooNE, microBooNE, SciBooNE, and MINERvA and be applicable to the MINOS, NOvA, and future Fermilab to DUSEL oscillation experiments.

Since the discovery of neutrino oscillations in 1996, there has been a world-wide experimental effort in particle physics to use oscillations to measure the fundamental properties of the neutrino and ultimately explore the possibility that neutrinos are responsible for the matter/anti-matter asymmetry in the universe. These experiments (K2K, MiniBooNE, MINOS, T2K, NOvA, and future experiments at a Deep Underground Science and Engineering Laboratory) require detailed knowledge of neutrino-nucleus interactions. Several experiments (MINERvA, SciBooNE, micro-BooNE) have undertaken measurement programs to improve our knowledge of neutrino-nucleus scattering. These experiments employ neutrino beams with a relatively large energy spread (“wide band”) and hence have little a priori knowledge of the incident neutrino energy.

The upcoming NOvA experiment will be the corner stone of the domestic high-energy physics program over the next decade and will search for neutrino oscillations using a newly-constructed detector in northern Minnesota. NOvA will use a narrow-band neutrino beam centered at 2 GeV. This narrow-band beam is unique and the a priori knowledge of the neutrino energy it provides has several advantages over the more common wide-band beams.

We propose to re-instrument the existing SciBar detector used by the now-completed SciBooNE experiment and place it in the NOvA 2 GeV narrow-band beam just in front of the NOvA near detector. The SciBar detector consists of approximately 15,000 scintillator bars that allow neutrino interactions to be imaged in fine detail. While the scintillator remains at Fermilab, the photodetectors and readout electronics were removed from the detector after decommissioning and taken to Japan for another experiment. The experimental neutrino group at the IU Cyclotron Facility has developed a system of photodetectors and electronics that are ideal for this application. This system was developed for a separate, yet similar, detector system. A 12-board system has been built at IUCF and is currently well-along in the commissioning stage. We are proposing to extend this system to 250 boards and use it for the SciBar detector.

The SciBar detector, running with new instrumentation in the NOvA narrow-band beam, will offer several advantages when reconstructing particular classes of neutrino interactions complementing measurements made in other beam lines. The narrow energy spread of the NOvA beam will allow for the suppression of backgrounds to measurements of quasielastic (QE) neutrino interactions. It also will allow for improved measurements of “neutral-current” (NC) interactions where a neutrino carries away some of the event energy undetected. In the region near 2 GeV, this detector would record a large sample of approximately 1 M events per year.

The program of measurements accessible with this detector will increase our knowledge of both neutrino interactions and neutrino oscillations. There is currently a puzzle in charged-current QE interactions where recent results do not agree with the data taken with bubble chambers in the 1970-80s. The source of this discrepancy is unknown; it may be due to poorly understood physics in the nucleus, nucleon, or due to experimental effects. A low-background measurement of QE scattering at 2 GeV with the SciNOvA experiment would fall exactly in the region between the current measurements and would help to better understand the situation. In addition, the physics of neutral-current interactions on nuclei may be investigated, yielding additional insight into these processes.

These measurements will also provide an important service for the neutrino oscillation measurements of NOvA for a relatively small investment of money and effort. Since the detector will be located in the same beam as the NOvA detector and will be composed of the same material (mostly carbon), this higher-resolution detector will enable a robust, data-driven estimate of the instrumental backgrounds to the electron neutrino appearance and muon neutrino disappearance searches, increasing the precision of those results from the NOvA program.

2 Neutrino Physics

The SciBar detector on the NOvA narrow-band neutrino will enable new insight on the physics of neutrino-nucleus interactions. The data would complement that of other experiments in this energy range and will be valuable additional information for both the underlying physics and for better understanding of neutrino oscillation background processes.

The event rates for the various charged- and neutral-current channels are shown in Table 1 and the interaction rate as a function of neutrino energy is shown in Fig.1. This energy distribution is particularly well-suited for several interesting physics channels.

	Charged-current	Neutral-current
elastic	220	86
resonant	327	115
DIS	289	96
coherent	8	5
total	845	302
$\nu + A \rightarrow \pi^0 + X$	204	106

Table 1: Event rates for elastic, resonant, deep-inelastic (DIS) and coherent neutrino scattering processes for one year of running in neutrino mode for the 10 kt SciBar fiducial volume. Units are 1000's of events. Event rates for inclusive π^0 production are also shown. Rates were calculated using the GENIE [1] neutrino generator.

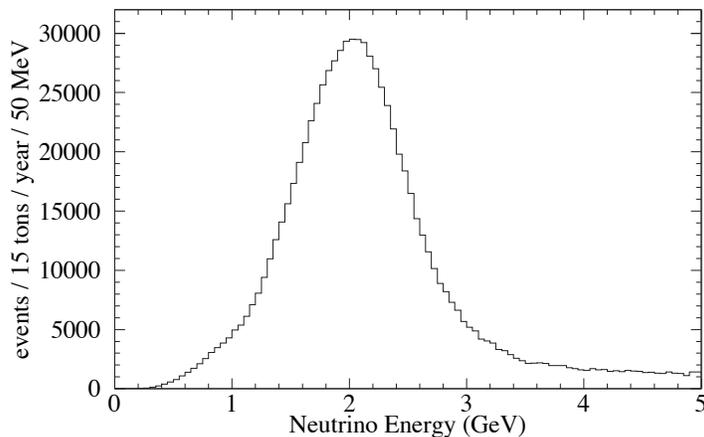


Figure 1: Event rate as a function of neutrino energy for a detector in the near hall in the NOvA narrow-band neutrino beam.

2.1 Charged-Current Quasielastic Scattering

A thorough understanding of the charged-current quasielastic scattering (CCQE) process of neutrinos on (bound) nucleons ($\nu + n \rightarrow \mu/e + p$ and $\bar{\nu} + p \rightarrow \mu/e + n$) in the 1 GeV energy region is important for neutrino experiments as it is the cleanest detection reaction for both appearance and disappearance searches. Ultimately, we need to completely understand the physics behind this interaction in order to make precision oscillation measurements.

A puzzle has recently arisen with the analysis of charged-current quasielastic ($\nu_\mu + n \rightarrow \mu^- + p$) data from the MiniBooNE experiment running on the FNAL Booster Neutrino Beamline (BNB). Results from previous CCQE experiments (for a recent review see Ref. [2]), performed predominantly with bubble chambers on light nuclei, yield an axial mass, $M_A = 1.03 \pm 0.02$ GeV [3]. The axial mass parametrizes the Q^2 (4-momentum transfer) evolution of the axial form factor. The MiniBooNE data contains more events at larger Q^2 (> 0.4 GeV²) than can be reconciled with this previously measured value of M_A . MiniBooNE has measured $M_A = 1.23 \pm 0.20$ GeV in an early analysis [4] and $M_A = 1.35 \pm 0.20$ GeV in a subsequent analysis [5].

The MiniBooNE value for M_A quoted above is extracted in an analysis that only considers the relative shape of the Q^2 distribution (as is typically done in this procedure). It may be that nuclear effects due to the binding of the target nucleons within carbon are the cause for this apparent disagreement with previous results that utilized mainly hydrogen or deuterium targets (see, for example, Ref. [6]). However, in a recent extraction of the absolute cross section for the CCQE process, MiniBooNE has reported total cross section values as a function of neutrino energy that are large compared to those calculated using $M_A = 1.03$ GeV. The measured total cross section is consistent to within 10% (the error on overall normalization) of the expected cross section with $M_A = 1.35$ GeV. Nuclear effects can give a larger effective M_A in the Q^2 shape of the data [7] but these effects reduce the total cross section, not enhance it. It may be that the larger measured M_A values in both Q^2 shape and reaction rate are a coincidence, but further investigation is warranted.

Recent results from other experiments have also added further information to the situation, but have not clarified it. Preliminary results from SciBooNE [8], using the SciBar detector in the FNAL BNB, also show a total CCQE cross section larger than that expected from $M_A = 1.03$. However, recent results from NOMAD [2] running at higher neutrino energies show total cross section values consistent with the previous world average M_A . The MiniBooNE, SciBooNE, and NOMAD results are shown together in Fig. 2. As is evident from that figure, it would be desirable to investigate the CCQE reaction in a beam of $E_\nu \approx 2$ GeV, exactly that of the NOvA narrow-band beam.

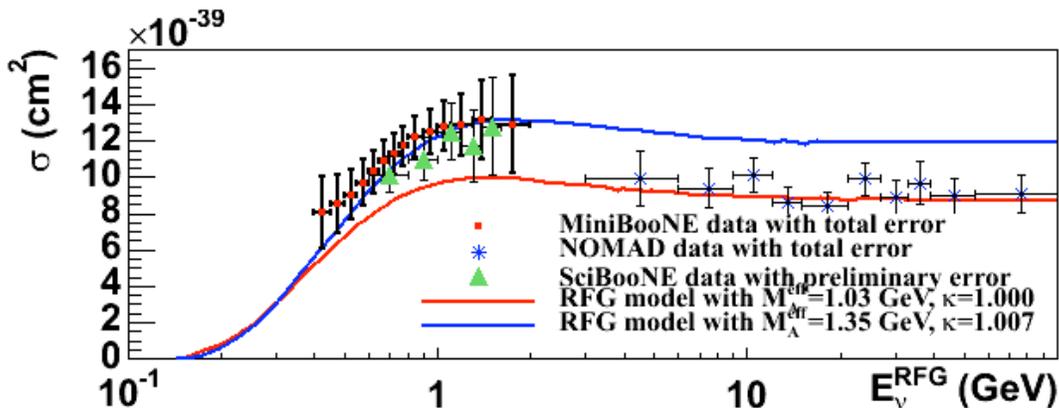


Figure 2: Preliminary measurements of quasi-elastic neutrino cross-section as a function of energy. No single model (red and blue lines) explains all the data.

Results from Q^2 shape analyses in other recent experiments on heavy targets also find higher M_A values than the world average. The K2K ($E_\nu \approx 1.3$ GeV) SciFi detector with a water target [9] finds $M_A = 1.20 \pm 0.12$ GeV and the SciBar detector in the K2K beam [10] finds $M_A = 1.14 \pm 0.11$ GeV. In addition, recent results from the MINOS ($E_\nu \approx 3$ GeV) near detector experiment on iron extracts $M_A = 1.26 \pm 0.17$ [11].

To clarify the current situation with the CCQE interaction, measurements need to be made

of the total cross section and Q^2 shape for a variety of nuclei. This will require a multi-pronged approach from multiple experiments. Each of the M_A measurements mentioned above are limited by systematic uncertainties. We expect that by running in a narrow band beam, the systematics of the QE measurement can be improved in two ways. First, the background to the QE sample can be reduced by anti-selecting events with the correct QE topology, but with large amounts of missing energy, indicative of final state particles that are absorbed by the nucleus and not seen by the detector. Second, as the peak energy of the narrow band beam is largely determined by pion decay kinematics, it is robust against large variations in the neutrino beam modeling. This will allow for stronger constraints on the absolute neutrino energy scale than is possible in a wide-band beam and improved calculations of the absolute neutrino flux. The MINERvA experiment will run with the on-axis (wide-band) NUMI beam and will provide valuable information on the CCQE process. The SciBar detector, which has already run on the BNB, in the NUMI off-axis (narrow-band) beam, will provide necessary and complementary information on the CCQE process.

2.2 Neutral Current Scattering

Neutrino neutral-current (NC) scattering ($\nu + N \rightarrow \nu + X$) is important for oscillation experiments as the NC process can contribute substantially to backgrounds for electron neutrino appearance – the primary measurements of the miniBooNE, T2K, NOvA, and LBNE experiments. This is true because of the large missing energy inherent in NC processes. A narrow-band beam reduces this problem and would allow an associated near experiment to produce NC measurements with reduced uncertainties. In addition to gaining better understand of NC processes for oscillation measurements, there are several other physics topics that may be pursued with NC processes.

2.2.1 Neutral Current π^0 production

Neutral-current π^0 production (NC π^0) in neutrino scattering ($\nu + N \rightarrow \nu + \pi^0 + X$) is a particularly thorny background for ν_e -appearance experiments, even though the event rate compared to other neutrino channels is fairly small. MiniBooNE has measured this process in order to obtain a better NC π^0 background measurement for the oscillation appearance search and in order to investigate coherent π^0 production in the NC process [12]. The MiniBooNE result shows the rate for coherent NC π^0 production to be substantially lower than prediction. In addition, SciBooNE has measured the coherent π^0 production process [13] in charged-current scattering and has found that to be lower than prediction as well. The conclusion from these results is that the coherent production of π^0 on carbon is not well understood theoretically at $E_\nu \approx 1$ GeV and merits further investigation. The SciBar detector running in a narrow-band beam can contribute to this. As the final state neutrino carries an unknown fraction of the energy in an NC interaction, the narrow-band neutrino beam is a key feature for understanding the kinematics of NC scattering.

2.2.2 Neutral Current Elastic Scattering

A measurement of the neutral current elastic scattering (NCel) process ($\nu + p \rightarrow \nu + p$) is sensitive to any isoscalar contributions (such as strange quarks) to the spin structure of the nucleon [14]. A measurement of NCel scattering in SciBar in the narrow-band NOvA beam could be sensitive to these contributions. A large challenge to this measurement at the NOvA near location (in any detector) is the large low-energy neutron background from neutrino interactions in the rock surrounding the detector. However, it may be that this background could be accurately measured and subtracted from the data. If successful, a neutrino measurement with the SciNOvA experiment could add valuable information to the nucleon spin puzzle.

2.3 Application to NOvA Measurements of Neutrino Oscillations

NOvA is a next generation neutrino oscillation experiment on the NuMI neutrino beamline optimized for the search for electron neutrino appearance in a muon neutrino beam. NOvA will search for this oscillation using both neutrino and anti-neutrino beam and will be sensitive to oscillations down to roughly 1%. Should this oscillation be observed, NOvA can use comparisons of the neutrino and anti-neutrino oscillation probabilities to determine the neutrino mass hierarchy and begin the study of the CP structure of the PMNS matrix. Additionally, NOvA will make precise measurement of muon neutrino disappearance, providing \mathcal{O} 1% measurements of the oscillation parameters $\sin^2 2\theta_{23}$ and Δm_{31}^2 .

To make these measurements, the NOvA experiment will construct two detectors of masses 222 tons and 15 kt 14 mrad off the NuMI neutrino beam axis separated by 810 km. The NOvA detectors are constructed of liquid scintillator contained in extruded PVC containers. The NOvA experiment selects electron-neutrino charged-current (ν_e CC) events with an efficiency of 35% while rejecting 99.9% of the neutral-current (NC) backgrounds. The NOvA near detector will be located in a new cavern to be excavated in 2012 0.994 km from the NuMI target. Measurements of neutrino interactions in this detector will be used as a basis for extrapolation of backgrounds to the electron neutrino appearance search using the far detector. The extrapolation is complicated by many factors. First, the neutrino fluxes at the NOvA near and far detector locations are not identical; second, the near detector has a large presence of un-oscillated muon neutrinos which are not present at the far site. Accounting for these differences requires knowledge of the neutrino flux, knowledge of the neutrino cross-sections, and knowledge of the detector acceptance and misidentification rates. This final piece can be very difficult to understand and model. The NOvA event selection algorithms are estimated to accept only 0.1% of NC events into the ν_e CC event sample and the NC events which are selected are on the tail of most distributions used to distinguish NC and ν_e CC events. Correctly modeling these tails is quite difficult. Using its near detector, NOvA expects to be able to predict the backgrounds to the electron neutrino appearance search with 10% systematic uncertainty.

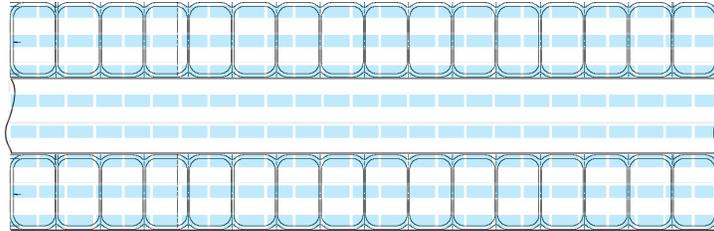


Figure 3: Comparison of the NOvA cell geometry (rounded boxes) to the SciBar cell geometry (light blue). Three planes of NOvA cells (two horizontal, separated by one vertical) are compared to 15 planes of the SciBar detector, which also alternate between horizontal and vertical readout directions. In the picture, the neutrino beam direction is directed from the top of the page toward the bottom.

In this EOI we suggest placing a re-instrumented SciBar detector in the NOvA near detector cavern directly in front of the NOvA near detector. The SciBar and NOvA detectors share many characteristics: both are nearly fully active scintillator detectors and both are composed almost entirely of hydrocarbons. Sharing the same composition and location ensures that the two detectors will have a common neutrino flux and have a common neutrino interaction cross-section. The only essential difference between the two detectors is their granularity: the NOvA detector samples

neutrino events using a cell size of 66 mm \times 41.6 mm whereas the SciBar detector samples in cells of 13 mm \times 25 mm. Figure 3 shows a comparison of the NOvA and SciBar granularity. As the two detectors will be exposed to an identical flux and have nearly identical neutrino cross-sections, it will be possible to use the fine grained SciBar detector to better constrain the detection efficiency and mis-ID probabilities in the NOvA detector and greatly reduce the need for Monte Carlo modeling of the backgrounds to the ν_e CC event selection.

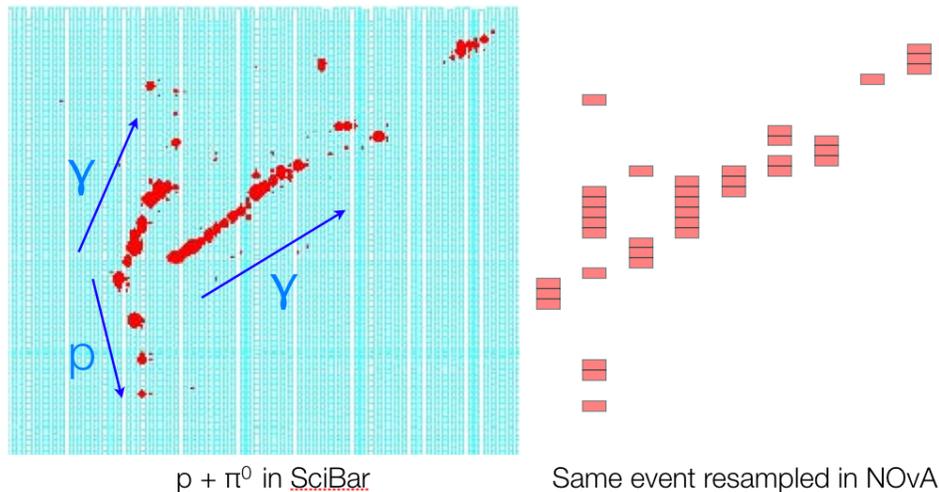


Figure 4: Comparison of a neutral-event containing a π^0 sampled by the SciBar detector (left) and the NOvA detector (right).

The principle of the technique is illustrated in Figure 4 which shows an NC event that is well resolved by the SciBar detector. In particular, the two showers resulting from $\pi^0 \rightarrow \gamma\gamma$ are clearly separated. On the right hand side of the figure the same event is shown, resampled according to the NOvA cell size. Many of the details which are visible in the SciBar detector are no longer visible in the NOvA detector. Using this process of resampling, it should be possible to take well-resolved ν_μ CC, ν_e CC, and NC events from the SciBar detector and input them directly into the NOvA reconstruction and event selection algorithms yielding an independent and essentially Monte Carlo-free estimate of the NOvA detectors particle ID performance. Using this technique, it should be possible to reduce the 10% estimated uncertainty in the near-to-far extrapolation of the backgrounds to the electron neutrino appearance search, extending the reach of NOvA's search for electron neutrino appearance.

Likewise we expect this technique to be useful to NOvA's measurements of $\nu_\mu \rightarrow \nu_\mu$ oscillations which are used to measure $\sin^2 2\theta_{23}$ and Δm_{31}^2 . In this case, NOvA primarily relies on the excellent neutrino energy resolution of quasi-elastic (QE) events ($\nu_\mu + n \rightarrow \mu^- + p$). The same resampling technique described above for NC events should be applicable to this channel, allowing for estimates of the non-QE backgrounds in the ν_μ CC-QE sample with little reliance on Monte Carlo simulations.

3 Experiment

We propose to transport the existing SciBar detector [15] to a position in front of the planned NOvA near detector experiment in the to-be-constructed cavern off of the MINOS near detector tunnel (Fig. 5.) The SciBar detector was one of three subdetectors used in the SciBooNE experiment [16] that ran in the FNAL Booster Neutrino Beamline (BNB) from June, 2007 until August, 2008. The

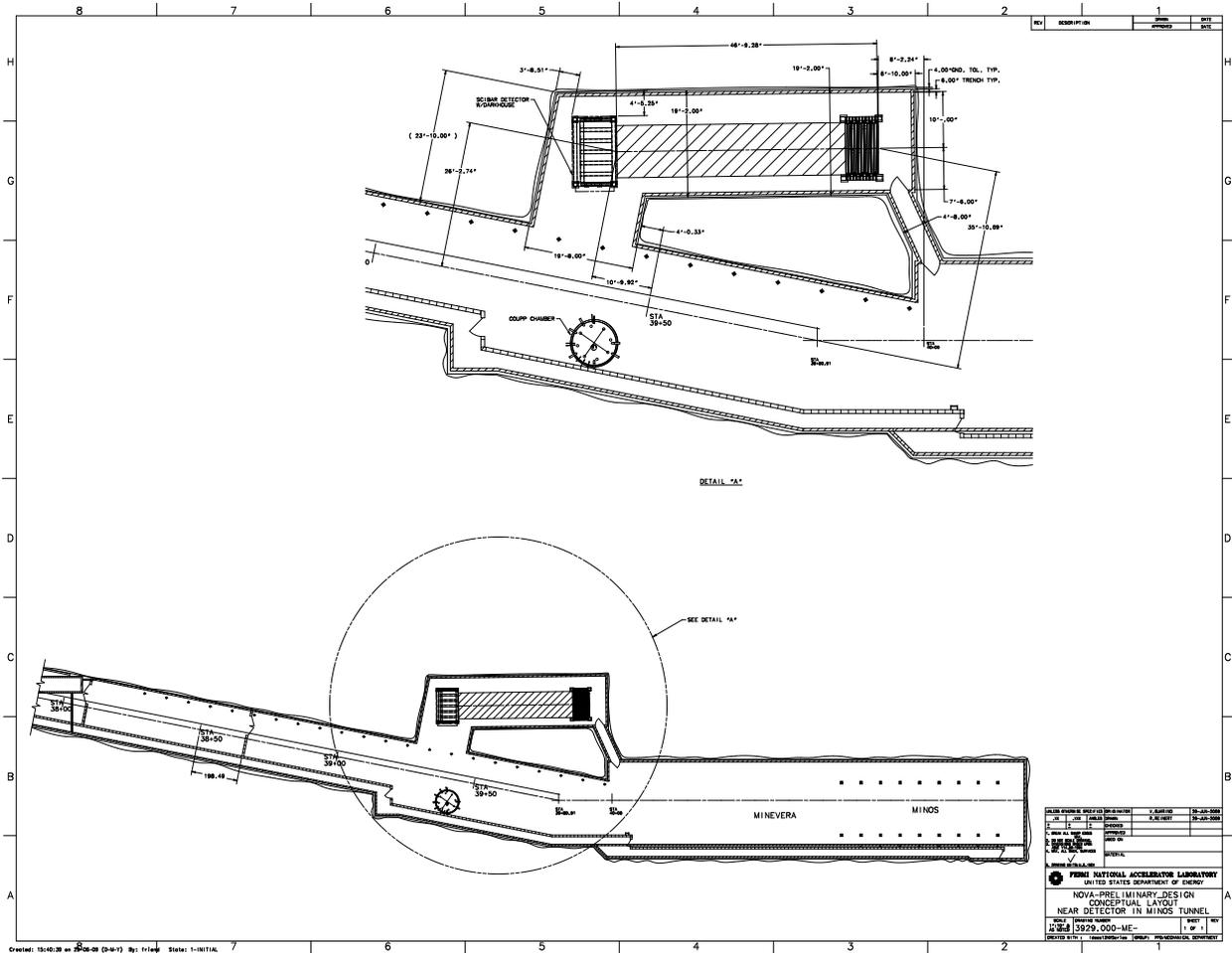


Figure 5: Plan view of the SciBar detector located in the NOvA near tunnel.

photomultiplier tubes and readout electronics have been removed from the SciBar detector and taken back to KEK where they will be used for another experiment. The SciBar detector, consisting of scintillator bars, wavelength-shifting fibers, and PMT-interface pieces would be reused for the SciNOvA experiment.

To accomplish this we would need to move the SciBar detector from its current location in the SciBooNE enclosure to the NOvA near-detector tunnel, procure new 64-anode PMTs, and build the readout electronics. This equipment and the associated tasks are described below.

3.1 SciBar Detector

The SciBar detector [15] consists of $\approx 15k$ extruded $1.3 \times 2.5 \times 290 \text{ cm}^3$ scintillator strips arranged in 64 layers. Each layer consists of an X and Y plane, each containing 116 strips. The total active volume of the scintillator is $2.9 \times 2.9 \times 1.7 \text{ m}^3$ with total mass of 15 tons. Each strip contains an embedded 1.5 mm diameter wavelength-shifting fiber which are routed to 64-fiber “cookies”. The fiber cookies are designed to interface to 64-anode PMT with 2 mm square pixels arranged in an 8×8 array. Approximately 250 PMTs are required for the SciBar detector. The detector, including the PMTs and readout electronics housing, is mounted in a FNAL-designed steel frame

and is enclosed in a dark box of approximate dimensions 4.1 m wide \times 4.2 m tall \times 2.3 m deep.

We propose to move this detector including the steel frame and darkbox from the current location in the SciBooNE enclosure to the NOvA near-detector hall. This would involve lifting it out the SciBooNE enclosure, transporting it to the MINOS assembly building, lowering it down the MINOS access shaft, and shuttling it into position in front of the NOvA near detector.

A short, preliminary study was conducted by FNAL PPD engineering in June 2009. This study indicates that there is adequate clearance to lower the SciBar detector down the MINOS access shaft. However, the clearance is not generous (only a few inches at several points) and further investigation is needed for a definitive answer. It may be that some modification of the SciBar frame or the location of utilities pipes in the shaft is required. There is adequate headroom at the top and bottom of the shaft. The detector total weight (30 tons) is too large to lift with the MINOS (15 ton) crane so some disassembly/reassembly of detector would be required or a larger crane lifting through the building roof would be utilized.

The plan (as known in June 2009) for the NOvA near detector hall indicates that there is adequate space for the SciBar detector in front of the NOvA near detector, however, interference with other support or scintillator containment structures should be identified. There are sump pump covers in the MINOS hall that would need to be identified and reinforced to allow the detector to be moved into position from the bottom of the access shaft.

The SciBar detector was lowered into the SciBooNE enclosure as a complete unit with a large crane, so no problems are anticipated extracting the detector from that enclosure.

3.2 New PMTs and Electronics

The SciBar detector currently located at FNAL consists of the scintillator, WLS fibers, and PMT interface. However, the PMTs and readout electronics have been relocated back to KEK and are not available for use with this detector at FNAL. We propose to replace the PMTs and readout electronics with a system that was developed at Indiana University (IU) for the FINeSSE experiment. A 12-PMT system has been designed and built and is in the commissioning phase at IU. This system could be replicated in order to provide the readout for the 250 PMTs required for the SciBar readout.

The proposed FINeSSE experiment [14] used a detector called scibath [17] consisting of \approx 19k WLS fibers immersed in liquid scintillator. In order to demonstrate the viability of this technique, an 800-fiber, 0.5 m³ prototype was built using Indiana University and NSF funding within the experimental nuclear physics group at the IU Cyclotron Facility (IUCF). This prototype included custom-built readout electronics for the 64-anode PMT. The high channel-count of this type of detector motivated a readout design using commodity (inexpensive) components to keep the costs low. This was facilitated by the fact that data rates from a neutrino experiments are low and do not require a fast parallel readout bus.

This effort has resulted in the production of the IUCF Integrated Readout Module (IRM). The IRM consists of a 6U VME board with an “integrated” 64-channel multianode photomultiplier (MAPMT). A photo of a completed board is shown in Fig. 6 and the readout architecture is shown in Fig. 7.

The signal from each of the 64 MAPMT channels is routed to a “ringing integrator” analog front-end circuit connected to a flash ADC running at 20 MHz. The ADC digitizes the PMT signal for approximately 1 μ s (20 samples) through the analog front end circuit which allows for both the charge and time information to be obtained via one ADC with no deadtime as is present in a “sample and hold” circuit. The ADC data is routed to a field programmable gate array (FPGA) which performs zero suppression, triggering, and channel-tagging. The FPGA buffers

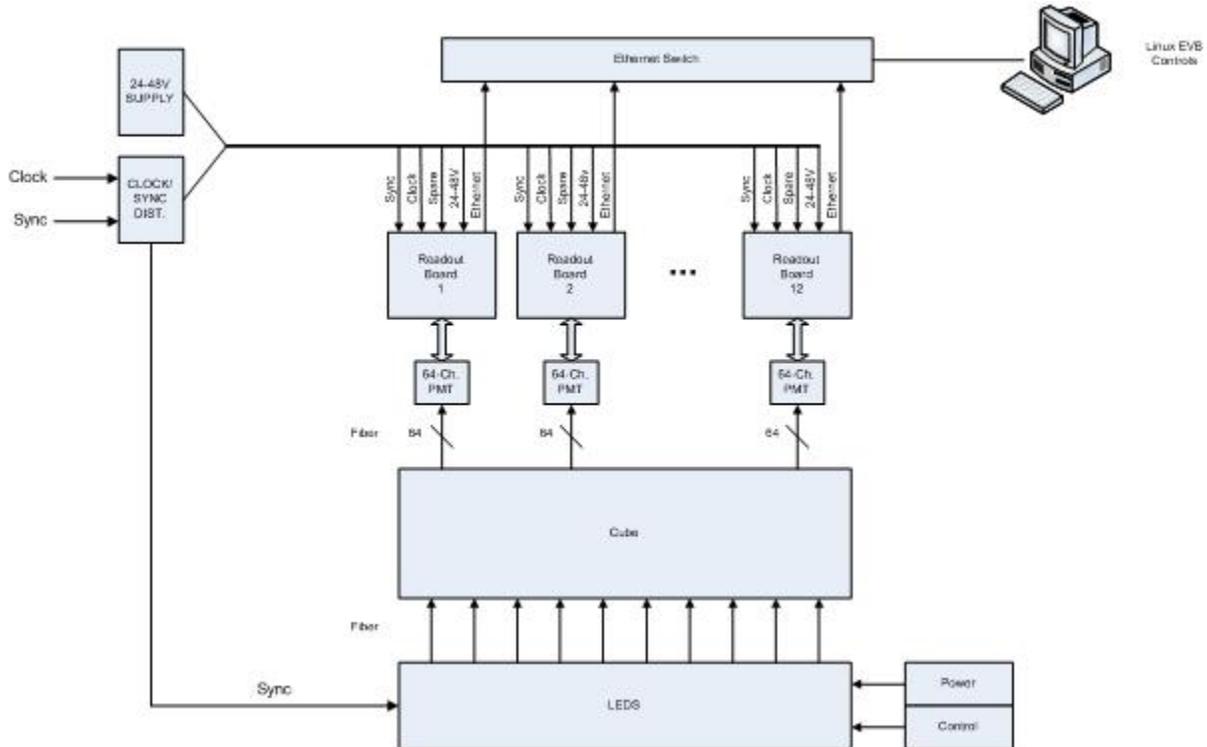


Figure 8: The IRM readout system.

data into memory where it is subsequently read by an ARM9 microprocessor. The microprocessor time-stamps and ships the data to an analysis computer via ethernet. This arrangement allows for fairly substantial on-board signal analysis and pattern recognition algorithms to be applied in quasi-realtime. Each board ships data to an analysis computer over 10 Mbit ethernet where the data will be subjected to sorting, further analysis, and archiving to disk.

The layout of the 12-board system attached to the prototype scibath detector is shown in Fig. 8. For a 250-board system, running with the SciNOvA detector, a similar scheme will be used. Data rates will be low since the neutrino beam duty ratio is quite low and there is much inter-spill time for data readout. If more CPU power is required for event-building or ethernet traffic within the 250-board system is too high, a “pyramid” structure of event building computers can be implemented.

4 Costs and Schedule

The costs for the PMTs and electronics required for this project are well understood since a 12-board system has already been built. The estimate for the IRM boards is \$49/channel which includes all connectors and PMT mounting hardware, but not the PMTs. We are pricing 250 (64-channel) boards which will provide readout of the SciBar detector with 7.5% spares. This results in an estimate of \$775k for the IRM boards needed to outfit the SciBar detector. Our current estimate for PMTs is \$1600 for each unit (\$25/channel), based on a recent price quoted by Hamamatsu for the model H8711. This yields an estimate of \$400k for the required 250 PMTs. We estimate and additional \$80k for a clock/trigger system (required for the IRM boards), low-voltage

power supplies, board mounting hardware, and computer equipment. This total for this readout equipment is \$1.255M. The estimated personnel costs (assuming IUCF rates) are \$390k. This includes time for electronics design (for small modifications to the current IRM design), mechanical engineering of required mounting structures for the electronics, software design, management of board procurement, and final board assembly/testing. Putting these numbers together with an overhead rate of 52% (IU's rate) yields a total project cost of \$1.75M. Some contingency is built into this number, but it need not be too generous as this project is based on hardware that has already been built. Additional costs for the project would need to be considered for relocating the SciBar detector to the MINOS hall and any mechanical design and fabrication for mounting the detector at the new location.

Our goal is to obtain approval soon so that funding may be procured in 2010 with electronics fabrication and PMT manufacture to start immediately after and continuing through 2011. If that process proceeds expeditiously, the detector could be installed and commissioned in 2012.

5 Conclusions

The addition of the SciBar detector to the NOvA near detector program in the narrow-band neutrino beam will enable additional insight on the physics of neutrino scattering. It may perhaps allow a resolution to the interesting apparent conflict of quasielastic data collected by the Mini-BooNE and SciBooNE experiments in the FNAL Booster neutrino beamline. It will also provide much needed information on the physics of neutral current scattering and direct constraints on instrumental backgrounds which will help with the NOvA neutrino oscillation program. The detector exists and may be moved relatively easily. The space in the near hall on the narrow-band NOvA beam may be allocated with little to no additional costs. The execution of this experiment would result in a efficient expansion in the physics obtained with the FNAL neutrino program.

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