

# Cosmic Ray capability of NO $\nu$ A

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**Abstract.** The NuMI Off-Axis  $\nu_e$  Appearance Experiment (NO $\nu$ A)[1] is a new large detector to be built in northern Minnesota along the Fermilab NuMI beam line in order to make further studies of neutrino oscillations at the atmospheric neutrino  $\Delta m^2$ . The design and goals of the experiment will be presented, along with some ideas for how it can be used to study cosmic rays.

**Keywords:** neutrino oscillations, cosmic rays

## I. THE DESIGN OF NO $\nu$ A

The NO $\nu$ A far detector will be the largest full acceptance surface calorimeter and tracking detector every built. Although it has not been designed as a cosmic ray detector, it will certainly have cosmic ray capabilities that are new and unique.

The detector will be composed of 385,000 cells of extruded PVC plastic in a cellular structure. Each cell is 3.9 centimeters wide by 6.0 centimeters deep and is 15.5 meters long. The cells are filled with a total of 3.3 million gallons of liquid scintillator. The liquid scintillator comprises 70% of the total detector mass, making this a totally active tracking calorimeter detector optimized for the identification of electron neutrino ( $\nu_e$ ) interactions. The detector is read out via 13,000 kilometers of 0.7 millimeter diameter optical wave-shifting fiber into 12,000 avalanche photodiodes with associated electronics. The 222 ton near detector, located at Fermilab in Illinois, will be constructed with components identical to the ones used in the far detector.

The basic unit of all the NO $\nu$ A detectors is a simple rectangular rigid PVC plastic cell containing liquid scintillator and a wavelength-shifting fiber. This is illustrated in Figure 1. The cross section of an extruded piece of PVC that is bought from the manufacturer is shown in Figure 3. Charged particles traverse the cell and scintillator light is produced in the liquid. The light bounces around in the rectangular cell of width W and depth D and length L until it is captured by a wavelength-shifting fiber or absorbed by PVC or scintillator. The fiber is twice the length L of the cell and is looped at the bottom so the captured light is routed in two directions to the end (top in the illustration) of the cell. At the top of the cell both ends of the looped fiber are directed to one pixel on an Avalanche Photodiode (APD) photodetector array and the light is converted to an electronic signal.

The NO $\nu$ A cell is made of a highly reflective titanium dioxide loaded rigid PVC cell with walls 2 to 4.5 mm thick. The cells have an interior width of 3.8 cm

transverse to the beam direction, an interior depth of 5.9 cm along the beam direction, and an interior length of 15.5 meters. The cell width and depth satisfy the scientific requirements and the cell length is sized to fit on a standard domestic 53-foot semi trailer truck. To achieve the 15 kiloton mass stipulated by the scientific requirements, we repeat the cell structure 385,000 times.

The low neutrino cross section, the long-baseline of the experiment, and the choice of an off-axis location each contribute to a small event rate for the NO $\nu$ A experiment. The experiment is made possible by a powerful beam at Fermilab, and a large detector. The mass of the far detector is planned to be 15,000 tons, and the area of the experiment is comparable to that of a football field. A schematic of the far detector is shown in Figure 4, along with two other detectors to be built on the Fermilab site. The 15 meters height means that it would be several interaction lengths for any cosmic ray hadrons which made it to the surface of the earth. The 5.9 cm cell size means that typical cosmic ray muons will traverse 250 or more cells as it passes through the detector. This provides an opportunity for cosmic ray studies.

The parameters of three NO $\nu$ A detectors are listed in Table 1.

## II. THE SCIENTIFIC GOALS OF NO $\nu$ A

The primary scientific goal of the NO $\nu$ A experiment is to extend the search for  $\nu_\mu \rightarrow \nu_e$  oscillations by roughly an order of magnitude beyond the sensitivity of the MINOS experiment. Depending on the value of the currently unknown neutrino oscillation parameter  $\theta_{13}$ , NO $\nu$ A can begin to study the mass ordering and search for the effects of the CP violating phase angle  $\delta$ . NO $\nu$ A is particularly well suited to the study of the mass ordering due to the large amount of earth between the neutrino source and the detector. No other approved experiment can attack this issue.

NO $\nu$ A plans to split its running time equally between periods with the horns focusing positive particles (neutrino running) and negative particles (antineutrino running). Even though the rates are higher for neutrino running than antineutrino running, there are two reasons for this strategy. First it makes the sensitivity to seeing a signal less dependent on the value of  $\delta$  and the sign of  $\Delta m_{32}^2$ . Second, without antineutrino running, NO $\nu$ A would have no ability to measure  $\delta$  or the sign of  $\Delta m_{32}^2$ .

The capabilities of the NO $\nu$ A experiment have been calculated assuming the 15 kT detector with both  $36 \times 10^{20}$ ,  $60 \times 10^{20}$ , and  $120 \times 10^{20}$  protons on target pot which reflect different run times and/or beam capabilities at Fermilab. The first corresponds to 6 full years (44 weeks per year) of running at 700 kW beam power, assuming the NuMI and accelerator upgrades included in the NO $\nu$ A project. The last two correspond to 6 full years of running at 1.2 MW and 2.3 MW beam power with the conceptual accelerator upgrades known as SNuMI and Project X. The sensitivity calculations have been done assuming a systematic uncertainty in the background extrapolation from the near to far detector of 10%. Figure 2 shows the sensitivity to  $\theta_{13} \neq 0$  at the three standard deviation level as a function of  $\delta$  for each of the mass orderings. A way of comparing the difference between 700 kW, 1.2 MW and 2.3 MW beam power is to note the fraction of the parameter space for which the NO $\nu$ A three-standard deviation sensitivity is more than an order of magnitude greater than the current best 90% CL upper limit which is from CHOOZ. The 700 kW, 1.2 MW and 2.3 MW running meets this criterion for 9.5%, 22% and 64% of the parameter space.

### III. THE COSMIC RAY CAPABILITIES OF NO $\nu$ A

The performance of the NO $\nu$ A detector using cosmic rays has not been studied with a full simulation. NO $\nu$ A is the first long-baseline neutrino experiment to be built near the surface of the earth, and one design criterion is that cosmic rays of any kind not provide a significant background to the beam signal, which is electromagnetic showers arising from electrons with energies near 2 GeV. Both timing and pattern recognition algorithms will be used to eliminate most cosmic ray initiated backgrounds, but the expected signal rate is quite small. In order to further reduce backgrounds from  $\gamma$ s in cosmic ray air showers, an overburden of nine radiation lengths of material is planned above the detector building in Minnesota. One of the initial goals of running an Integration Prototype Near Detector at the surface near Fermilab is to validate calculations and simulations of cosmic ray backgrounds in such a detector.

With such a large detector, it is natural to ask what other cosmic ray physics can be performed. Here we list ideas that might be studied:

- Supernova Neutrinos
- Upward going atmospheric neutrinos
- Multiple muons
- Single and multiple hadrons in EAS and their correlations
- Horizontal muons from neutrino interactions deep in the atmosphere
- Fluctuations in air shower components
- Coincidences with an air shower array (not yet designed or planned)

The NO $\nu$ A collaboration welcomes suggestions and ideas for the use of the NO $\nu$ A far detector for cosmic

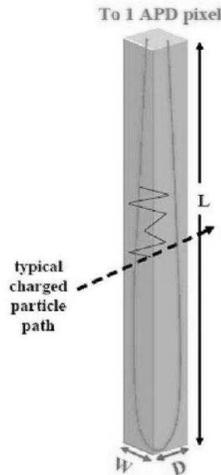


Fig. 1. A PVC cell containing liquid scintillator and wavelength shifting fiber. A charged particle incident on the front face produces light that bounces off the cell walls until absorbed by the fiber. The fiber routes the light to an APD.

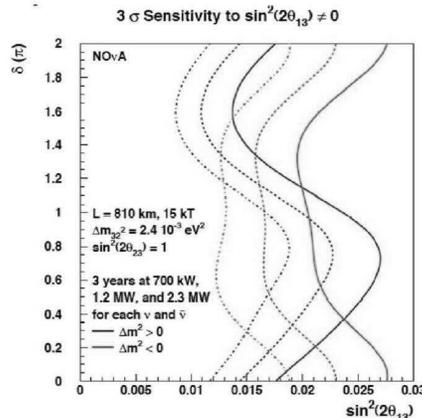


Fig. 2. Three standard deviation sensitivity for NO $\nu$ A to a non-zero  $\theta_{13}$  as a function of the unknown CP-violating phase  $\delta$ .

ray studies.

### REFERENCES

- [1] Fermilab E929, Proposal for the NuMI Off-Axis  $\nu_e$  Appearance Experiment, March 21, 2005.

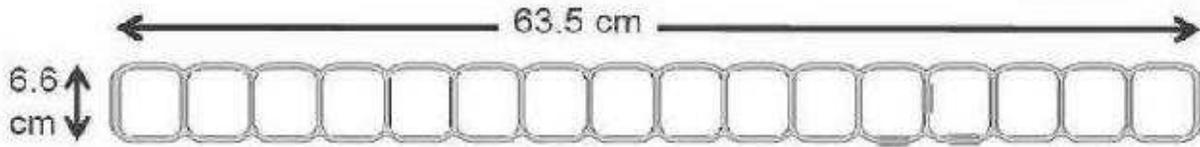


Fig. 3. Cross section of the NOνA extrusion, made of PVC plastic.

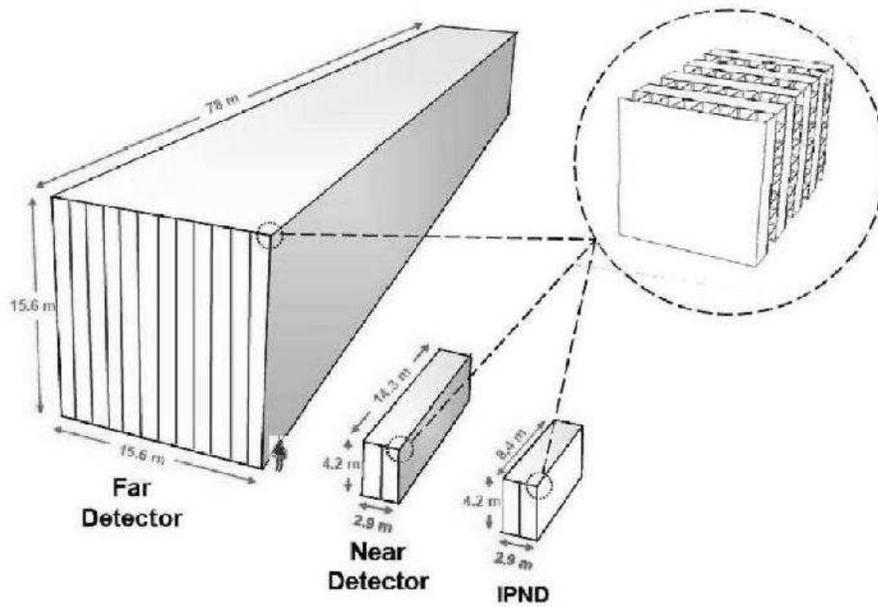


Fig. 4. A schematic of the three NOνA detectors

	Integration Prototype Near Detector (IPND)	Near Detector	Far Detector
Mass (metric tons)	84	222	15,000
Active Detector Size (width, height, length) in meters	(2.8, 4.1, 8.4)	(2.8, 4.1, 14.3)	(15.6, 15.6, 66.9)
Liquid scintillator required (gallons)	18,700	30,000	3,210,000
Number of 32 cell extrusion modules required	310	496	12,036
Number of extrusion modules seen by beam (horizontal by vertical)	3 by 2	3 by 2	12 by 12
Number of detector channels	9,892	15,904	385,152

TABLE I  
TABLE I: PARAMETERS OF THE THREE NOνA DETECTORS.