Neutrino Oscillations at the Intensity Frontier: The NOvA Experiment

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Abstract. The “NuMI Off-Axis electron-neutrino Appearance” (NOvA) is a second generation, long- baseline, neutrino oscillation, experiment. It is made of two detectors, a large Far detector (14 ktons) and a similar Near detector (222 tons), both made of mostly active scintillator and separated by 810 km. Along with the 700 kW NuMI-beam upgrade (a prelude to the Intensity Frontier), it will be the leading neutrino experiment at Fermilab. In the wake of the recent measurement of the $\theta_{13}$ mixing angle, NOvA is positioned to see evidence of the neutrino mass hierarchy, possibly to resolve the $\theta_{23}$ octant ambiguity, and begin the study of the CP violation at the lepton sector. The experiment is under construction. The design and potential of this experiment is presented here along with the current status.

1. Introduction

The last two years have been an exceptional time for neutrino physics. Several experiments have measured for the first time a non-vanishing value for the mixing angle $\theta_{13}$. These are accelerator driven electron-neutrino appearance measurement like the Japan-based T2K [1] and the USA-based MINOS [2], or nuclear reactor driven anti-neutrino disappearance ones, like the China-based Daya Bay [3], with strong evidence of reactor electron antineutrino disappearance consistent with neutrino oscillations and the France-based Double Chooz [4] with the most recent measurements to date. They progressively defined the value of $\theta_{13}$ to within a non-zero value-band around 9° with various confidence levels each (based on their systematics and the assumptions in the models). This large value makes it more possible to explore CP-violation and the mass hierarchy of the neutrinos. Now, we can address some of the compelling questions of neutrino physics and the lepton sector. What is the neutrino mass hierarchy? Do neutrino oscillations violate CP symmetry? Is the $\theta_{23}$ mixing angle 45° (maximal)? Do these findings indicate new symmetries or new selection rules, forces, sectors?

The Physics community has come together in several instances over the past few years trying to decide on the path for the next generation and further in the future experiments. Work on the Physics Frontiers [5] of Intensity, Energy and the Cosmic frontier, will provide answers, or better yet, will over-constrain the above parameters in order to determine any new physics beyond the Standard Model.

2. The NOvA Experiment

The second generation of the long baseline, accelerator based, neutrino oscillation experiments, is
made up of three experiments; the MINOS from Fermilab at 790km baseline, the T2K from JPARC at 293 km, and the NOvA Experiment, also from Fermilab at 810 km. The NOvA experiment aims to lead in the measurement of appearance of electron neutrinos and anti-neutrinos from the NuMI (Neutrinos at the Main Injector) neutrino beam from Fermilab (Fermi National Accelerator Lab in Batavia, Illinois, USA). The NOvA neutrinos are produced by a 120 GeV proton accelerator complex at 400 kW with a scheduled upgrade to 700 kW. After the protons fall on a graphite target, a secondary beam of pions and kaons is generated. In order to focus this beam, we use magnetic horns. By passing current through these horns, the charged-particles of the secondary-beam can focus forward. They can also control the consistency neutrino or anti-neutrino) of the tertiary beam by the direction of the current. That is the method used to create the anti-neutrino beam. Further downstream, the experiment is made of two functionally identical detectors positioned off-axis by 14 mrad. This angle yields for the resulting neutrino beam, a much tighter energy distribution in the spectrum, compared to an on-axis orientation (fig.1). The reduced flux is peaked about 2GeV within 20% in energy. For this peak energy, the first oscillation maximum falls at the distance of the NOvA-Far detector.

2.1. NOvA Detector Design
The basic design of a NOvA detector cell is long extruded PVC (plastic) tubes/cells, 4x6 cm in cross-section, with a length of 15 m for the Far and 4 m for the Near detector. Each is filled with a mineral oil liquid scintillator, instrumented with a single wavelength shifting fiber, and read out by an Avalanche Photo-Diode (APD). This provides a 64% active-material and low-Z calorimeter with a radiation length of X0~38 cm and tracking capabilities. This technology is optimal for electromagnetic shower reconstruction as well as muon tracking.

The near detector design calls for about 18,000 such cells, totaling 222 tons, positioned at a distance of 990 m from the NuMI beam target. The Far detector is much larger, numbering about 370,000 cells for 14 ktons, and at a distance of 810 km located in Ash River, Minnesota.

The detectors are instrumented by regions. They are synchronized and readout at high speed, continuously and with no dead time. The threshold is set to that of a half of a minimum ionizing particle energy deposition at the far end of the longest cell. This is equivalent to an energy threshold of about 6-8 MeV. All data is buffered in a large computing farm and triggered on asynchronously by the NOvA data acquisition and the Accelerator Trigger Systems. In figure 2, there are event displays of some indicative, simulated event topologies of the Near detector response to the prominent signatures of the NOvA experiment. A 48% reconstruction efficiency of 2 GeV electron-neutrinos from charge-current quasi-elastic scattering and a 1% rate of fake neutral-current interactions, with the proton recoil visible to few MeV, make the NOvA detection system an exceptionally good detector for its size.
2.2. The NOvA measurement

The NOvA experiment is designed to measure independently four probabilities of oscillation between the muon and electron neutrinos as they travel from the Near detector site to the Far detector 810 km away. We will combine the measured probabilities to evaluate the $\theta_{13}$ and $\theta_{23}$. Through these measurements, we can determine the mass hierarchy and the octant of the $\theta_{23}$, providing we have enough statistics (3-year data run that can restrict the $1\sigma$ and $2\sigma$ curves as in figure 3). Depending on the combination of the hierarchy and CP-violation, we can resolve them up to 38% of the phase space. This means we may be able to see the first evidence of CP violation in the lepton sector.

![Event topologies of simulated events in the Far detector for various signature interactions of 2 GeV neutrinos. Muon tracks are well differentiated from showers for reconstruction.](image)

Accepting the value for the $\theta_{13} \sim 9^\circ$, we can parameterize the bi-probabilities of appearance measured at the NOvA experiment in the plot of figure 3 between assumptions of $\theta_{23}$ and all the values of the CP-violating parameter. This particular plot assumes that the $\theta_{23}$ is maximal. A NOvA measurement is represented by a star in the plots. The curves around it represent 1$\sigma$ and 2$\sigma$ resolution after a 3 year run with neutrinos and anti-neutrinos each. The measurement (star) will fall on one of the eclipses representing the CP violation case and the mass hierarchy. Depending on that point, the NOvA may be able to resolve the hierarchy with up to 2$\sigma$ resolution and indicate the extent of CP violation (see fig. 3). This is the most optimistic of the scenarios. If the measurement (star) falls in some point in an eclipse for which the resolution circles overlap with larger parts of these eclipses, then a bound can be set. If the $\theta_{23}$ is sufficiently non-maximal, its octant may be resolved easier than the mass hierarchy. There are several other scenarios that span the phase space but their presentation is not for the short present document.

2.3. NDOS prototype

The Near Detector On the Surface (NDOS) is the prototype of a NOvA Near detector. The NDOS
was built for component production, installation and integration experience. It has been completed
since May 2011. It is positioned at a crossing of the beams from both the Main Injector (110 mrad off
axis) and the Booster accelerators (on-axis but 23° rotated). It is also situated 100 m above the beams
(i.e. on the surface). Until May 2012, it was doing physics runs when the NuMI beam was shut down
for the upgrade. It is planned to pick up again after NuMI beam resumes in April 2013. In the
meantime, it is used for engineering runs. These serve to evaluate hardware and software technology
tests. The data acquisition and the detector control systems (hardware and software) have been using
the NDOS as a life size test-stand for their developments. APD technologies are currently being
evaluated before being widely deployed on the Far detector in the winter of 2012. The track and vertex
reconstruction software have been using the NuMI and Booster beams to create extensive libraries of
good events. Cosmic muons are also used but for background rejection algorithms. All these signals
are also used to calibrate the detector. By measuring the attenuation length in the cells and the
spectrum of Michel electrons, we get exceptional resolution and low readout thresholds.

3. Current Status of NOvA
The Far detector laboratory has been completed and the NOvA project got beneficial occupancy since
April 2011. It is located at Ash River, Minnesota. It is on the surface with 3 m earth equivalent
overburden above the detector hall. The detector construction has started as of late summer of 2012.
Construction of the full 14 ktons detector is expected to be completed in 2014. The Near detector
cavern is being prepared and the detector completion is expected by 2014 as well. The NuMI beam
upgrades are on schedule to begin delivering the new beam power by the accelerator restart in Spring
of 2013.

4. Summary
The next decade will be the time that some of the most important questions of neutrino physics can be
answered. The NOvA experiment will be in the position to answer some of them. It has the
opportunity to resolve the mass hierarchy and the octant of 023, if it runs at least for 3 years on
neutrino and anti-neutrino beams. Most importantly, it could show some first evidence of CP violation
in the lepton sector. The experiment is well prototyped by now and well understood. It is also on track
in construction for the Far and Near detectors and the beam upgrades will provide it with the best
chance to lead the way in understanding the lepton sector and beyond.

References
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