

Status of NOvA

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Abstract. NOvA is a long-baseline neutrino oscillation experiment looking for the appearance of electron neutrinos and anti-neutrinos in the NuMI neutrino beam. It is comprised of a near detector located on-site at Fermilab, approximately 1 km from the neutrino source and a far detector located 810 km from the source in northern Minnesota. Both detectors are positioned 14 mrad off the beam axis to observe a narrow range of neutrino energies peaked at 2.2 GeV. Construction of the NOvA experiment has begun and the details are outlined below.

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NEXT GENERATION NEUTRINO OSCILLATION EXPERIMENT

The current generation of neutrino oscillation experiments has been quite successful in describing the disappearance of neutrinos from the Sun, atmosphere, nuclear reactors and man-made accelerator beams. These experiments include Super-K, Soudan II, KamLAND, K2K, MINOS, and SNO [1]. They have shown that the neutrino mixing matrix, known as the PMNS matrix, can be written as the product of three matrices. The first describes the oscillations corresponding to the atmospheric neutrinos, the second contains cross-terms including information on the mixing of electron neutrinos and muon neutrinos, and the third describes the oscillations corresponding to the solar and reactor neutrinos. They have also shown that oscillations are dominated by two mass-squared splittings, the atmospheric splitting $\Delta m_{32}^2 = 2.43 \times 10^{-3} \text{ eV}^2$ [2], and the solar splitting $\Delta m_{21}^2 = 7.56 \times 10^{-5} \text{ eV}^2$ [3]. In addition, the relative probabilities of the various mass states to interact as a given flavor state is also well described, except for the probability of ν_3 interacting as an electron neutrino.

Despite these successes, many questions still remain to be answered about neutrinos and their oscillations. For example, could there be more mass states than those that couple to the active flavors? That is, perhaps there are mass states that most strongly couple to a sterile neutrino which does not interact through the W and Z bosons. Additionally, we do not know the probability for a muon neutrino to transition to an electron neutrino, which is coupled to the size of the mixing angle θ_{13} . We also do not know whether CP violation occurs in neutrino oscillations such that the probability for the transition of one flavor into another is the same for neutrinos and anti-neutrinos. Another unresolved question, known as the hierarchy problem, is whether the third mass eigenstate,

ν_3 , is the heaviest or the lightest.

NOvA is designed to answer many of these questions. It will look for the transition of muon (anti-)neutrinos into electron (anti-)neutrinos using the long baseline experimental design. It consists of a near detector located near the neutrino source on the Fermilab site, and a far detector located 810 km away in northern Minnesota. The primary physics goals of the experiment are to measure θ_{13} , determine the ordering of the mass hierarchy, and measure the CP violating phase δ .

THE NUMI BEAM

The neutrinos will be produced using the NuMI beam which services the currently operating MINOS and MINERvA experiments. The beam has operated since 2005 and currently delivers a total power of 280-330 kW. The 120 GeV protons are delivered to the graphite target in 10 μs spills that come every 2.2 seconds. The pions and kaons produced when the protons interact in the target are focused using two magnetic focussing horns. The polarity of the horns can be adjusted to focus primarily positively or negatively charged hadrons which then decay into muon neutrinos or anti-neutrinos. The experiment will run for 6 years, 3 years using the beam in neutrino mode, and 3 years in anti-neutrino mode.

The NuMI beam will be run in the medium energy configuration for the NOvA experiment, producing a beam of neutrinos whose peak energy is 7.5 GeV for those neutrinos produced along the beam axis. The NOvA detectors are placed 14 mrad off the primary beam axis in order to produce a narrow band beam of neutrinos whose energies are peaked at 2.2 GeV. The off-axis location allows the experiment to capitalize on pion decay kinematics that produce a narrow range of neutrino energies no matter the parent energy of the pion. Figure 1 shows expected energy spectra for the medium en-

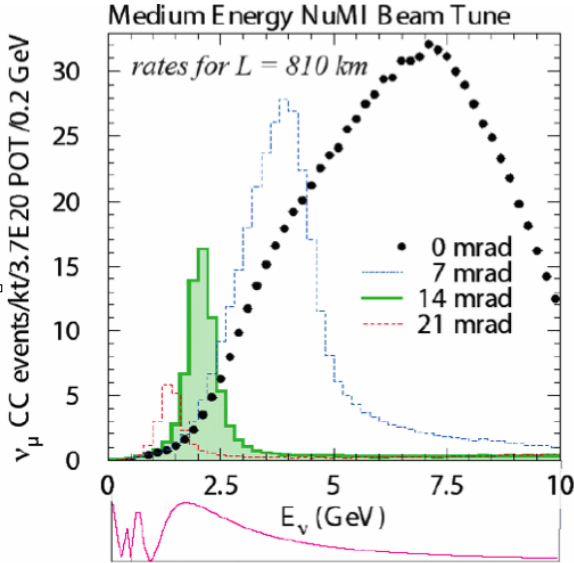


FIGURE 1. Medium energy on-axis NuMI beam spectrum and several off-axis spectra. The lower panel shows the oscillation probability as a function of neutrino energy for a baseline of 810 km.

ergy beam as well as several off-axis configurations. The 14 mrad off-axis configuration produces a beam whose peak energy corresponds to the oscillation maximum for the experimental baseline.

In addition to changing the beam configuration from the current low energy tune to the medium energy tune, several upgrades of the accelerator complex are planned to improve NOvA's sensitivity to its physics goals. The beam power will be increased to 700 kW by lowering the cycle time from 2.2 s to 1.33 s. This will be accomplished by slip stacking in the Recycler. Additionally, the intensity per cycle will be increased using a new injection kicker that allows 12 Booster batches instead of the current 11. Additionally the target and focussing horns will be upgraded to handle the increased power.

NOvA DETECTORS

The NOvA detectors are functionally identical detectors, using the same materials in each one. The basic element of the detectors is a PVC extrusion that has 15% TiO_2 in it to increase reflectivity. The extrusions are 6 cm wide in the beam direction and 3.87 cm wide in the transverse direction. The length of the extrusions depends on which detector they are in; far detector extrusions are 15.7 m long while the near detector extrusions are either 2.64 m or 3.92 m long. The size of the extrusions in the beam direction corresponds to 0.15 radiation lengths making the detectors fine-grained sampling calorimeters.

The extrusions are filled with liquid scintillator that is made of mineral oil containing 5% pseudocumene and some wave shifters. The scintillator will produce 30 detectable photoelectrons from the far end of an extrusion in the far detector. The scintillation light is delivered to the avalanche photo-diode (APD) detectors using wavelength shifting fibers. The APDs have 85% quantum efficiency and a gain of 100. They are cooled to -15 centigrade to reduce dark noise to 2 photo-electrons, and have a total noise of 4 photo-electrons.

The total mass of the far detector is 14 kt, with 70% of the mass in the scintillator and the remainder in the PVC. The far detector is 67 m long, corresponding to 930 planes. It is located in a building that is slightly below grade to provide approximately 3 m equivalent earth overburden once it is covered with barite and concrete. The building is designed to provide full containment of the scintillator in the event of a catastrophic failure of the extrusions to contain the scintillator. The far detector building is complete and nearly ready for beneficial occupancy at the time of writing.

The near detector will be located on site at Fermilab in a new alcove excavated near the MINOS near detector hall, 100 m underground. It has a total mass of 210 t, with a fiducial mass of 20 t. The detector has a steel muon catcher made of ten 10 cm thick planes of steel on the downstream end of the detector. The muon catcher allows the detector to contain up to 2 GeV muons.

The parts of the near detector have all been manufactured and the detector assembled on the surface at Fermilab. This prototype detector was used to test the construction and integration of the system. The construction took place over the summer of 2010 and the scintillator filling was done in October 2010. The detector will see a very off-axis beam from NuMI at 107 mrad and an on-axis Booster neutrino beam. It has already observed cosmic ray muons. Figure 2 shows an aerial view of the detector.

The NOvA schedule for completion of the detectors and beam upgrades has been accelerated over the last 1.5 years. The far detector construction will begin in July 2011. An accelerator shutdown is planned at Fermilab starting in March 2012 to perform the required beam upgrades. The 700 kW beam is expected to turn on in February 2013; at that time the far detector will be 2/3 completed, with the remaining work to be finished by fall 2013.

PHYSICS SENSITIVITIES

The NOvA sensitivity for detecting a non-zero value of θ_{13} at the 3σ confidence level (CL) is shown in Fig. 3. This figure shows the sensitivity as a function of the value $2\sin^2(\theta_{23})\sin^2(2\theta_{13})$ and the CP violating phase δ . The solid lines reflect a beam power of 700 kW, and

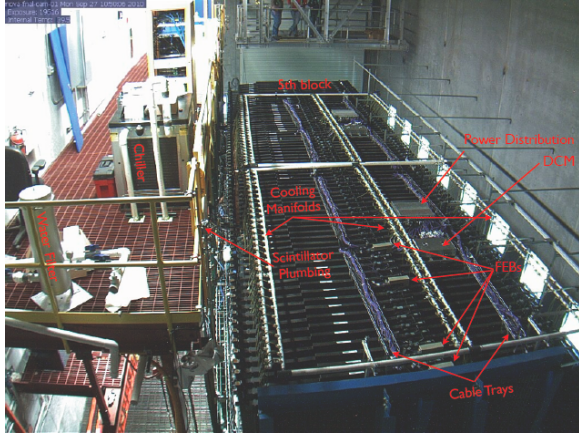


FIGURE 2. The prototype near detector assembled on the surface at Fermilab.

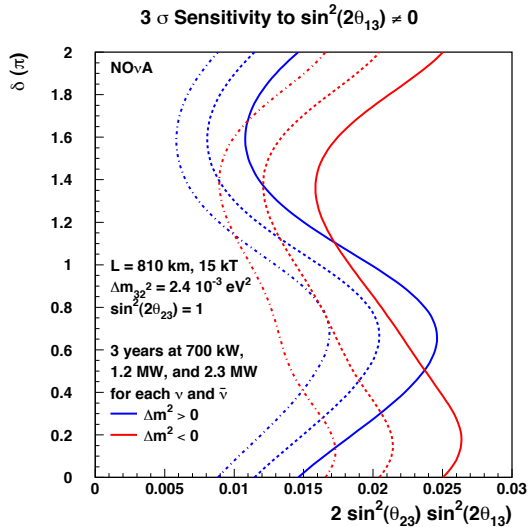


FIGURE 3. Sensitivity for detecting a non-zero value of θ_{13} .

the blue lines indicate a normal mass hierarchy. The beam is assumed to run for three years each in neutrino and anti-neutrino mode and the detector mass is assumed to be 15 kt. NOvA can detect a non-zero value of θ_{13} for the entire range of δ if $2 \sin^2(\theta_{23}) \sin^2(2\theta_{13}) > 0.027$ in either hierarchy.

The ability of NOvA to resolve the mass hierarchy as normal at the 95% CL is shown in Fig. 4. The hierarchy can be resolved if the CP violating phase is between $\pi < \delta < 2\pi$ for values of $2 \sin^2(\theta_{23}) \sin^2(2\theta_{13}) > 0.07$. If information from T2K, which has a shorter baseline and experiences less matter effect, is included the normal mass hierarchy can be resolved for all values of δ for $2 \sin^2(\theta_{23}) \sin^2(2\theta_{13}) > 0.15$.

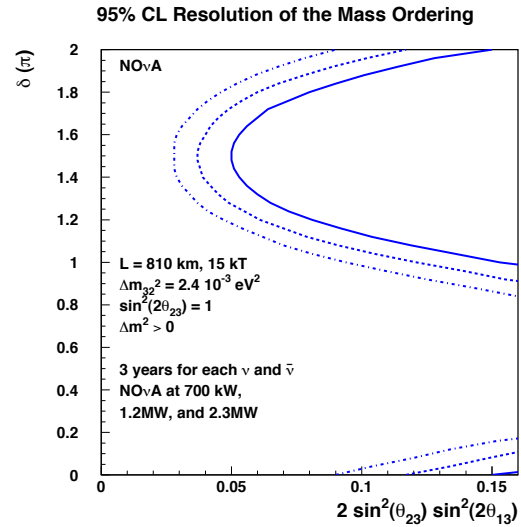


FIGURE 4. Sensitivity for determining the mass hierarchy is normal.

CONCLUSIONS

NOvA is poised to answer several important questions about neutrino oscillations. Its prototype near detector has been completed and is taking data. The far detector building is nearly ready for beneficial occupancy and the far detector construction is expected to begin in July 2011.

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