Snowmass2021 Letter of Interest: Expected Final Sensitivity of the NOvA Experiment to 3-Flavor Neutrino Oscillations

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■ (NF1) Neutrino oscillations
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□ (NF7) Applications
□ (TF11) Theory of neutrino physics
■ (NF9) Artificial neutrino sources
■ (NF10) Neutrino detectors
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Abstract

NOvA is a current-generation long-baseline neutrino oscillation experiment which observes ν_μ disappearance and ν_e appearance using neutrinos (or antineutrinos) of $\langle E_\nu \rangle \sim 2\,\mathrm{GeV}$ at a baseline of 810 km. Present NOvA measurements of the mixing parameters θ_{23} (7.0%) and $|\Delta m^2_{32}|$ (2.9%) are of good precision, comparable to the rest of the current experiments, while NOvA's constraints on the neutrino mass hierarchy (sign of Δm^2_{32}) and whether the value of the CP-violating phase δ_{CP} indicates CP violation, are currently only at the 1σ level. Mild tension between the preferred oscillation parameters of NOvA and T2K highlights the potential need for measurements at multiple neutrino energies and baselines in disentangling any degeneracies that may be present. This Letter presents the future predicted sensitivity of the experiment based on the expected future beam exposure factoring in the planned beam improvements and current analysis methods. Under this assumption NOvA projects 95% confidence measurements of the hierarchy for 45-60% of the δ_{CP} range as well as 2σ sensitivity to CP violation for 20-30% of δ_{CP} values, with up to 5σ sensitivity for resolving the mass hierarchy under specific parameter combinations.

1 Introduction

Measurements of neutrino oscillations by experiments at distances of hundreds of km from the neutrino source constrain the elements of the Pontecorvo-Maki-Nakagawa-Sakata mixing matrix, as well as the differences between the squares of the eigenvalues of the mass eigenstates [1–9]. Using neutrinos in the few-GeV range, contemporary long-baseline experiments are probing the currently least constrained parameters: the atmospheric mixing angle θ_{23} and mass splitting $|\Delta m^2_{32}|$, the ordering of the second and third mass eigenstates $\text{sign}(\Delta m^2_{32})$ (the neutrino mass hierarchy) , and the CP-violating phase δ_{CP}.

2 The NOvA Experiment

NOvA [10] is a 810 km baseline neutrino oscillation experiment whose neutrinos are sampled from the NuMI beam [11], produced at Fermilab. Neutrinos are observed at two locations in the experiment: at the 300 ton Near Detector (ND), 100 m underground at Fermilab; and the 14 kton Far Detector (FD), located on the surface in Ash River, Minnesota. Each detector is composed of liquid scintillator-filled PVC cells of cross-sectional area 3.9×6.6 cm and length 15.5 m (FD) or 3.9 m (ND) [12;13]. NOvA has recorded and analysed a beam exposure of 12.5×10^{20} protons-on-target (POT) of antineutrino data and 13.6×10^{20} POT of neutrino data. During these periods, the proton source achieved a peak hourly-averaged power of greater than 750 kW. NuMI is currently undergoing a staged improvement program which will enable beam powers up to 900 kW.

3 Measurements of 3-flavor oscillations in NOvA

NOvA observes 3-flavor oscillations through muon-neutrino disappearance (sensitive to $\sin^2 2\theta_{23}$ and $\left|\Delta m^2_{32}\right|$) and electron-neutrino appearance (sensitive to $\sin\theta_{23}$, Δm^2_{32}, and δ_{CP}) using both neutrino and antineutrino beams. NOvA selects candidate charged-current (CC) ν_e and ν_μ events interacting in the detectors using a machine learning classifier called CVN [14]. CVN efficiently discriminates between CC ν_e and ν_μ reactions, backgrounds from neutral-current reactions, and cosmic-ray backgrounds in the FD with a purity of 96% (97%) for ν_μ ($\bar{\nu}_\mu$) and 74% (64%) for the ν_e ($\bar{\nu}_e$) [15]. (The foregoing figures treat both ν_μ and $\bar{\nu}_\mu$ as signal for either beam mode, while only appeared ν_e ($\bar{\nu}_e$) in (anti)neutrino beam are counted as signal.) In CC ν_μ candidates the energy is reconstructed from muon candidate range, combined with a calorimetric measurement of the hadronic system. For CC ν_e candidates only the calorimetric approach is used.

The observed ν_μ spectra at the ND are subdivided by their reconstructed hadronic energy fraction E_{had}/E_ν and lepton momentum transverse to the beam direction p_T^μ in order to isolate populations with the best energy resolution and ND-FD similarity without limiting the measurements' statistical power. Discrepancies between the prediction and the observed data in the reconstructed E_ν spectra of these subsamples are used to correct the underlying true neutrino spectra and then extrapolated to the FD baseline, accounting for the beam divergence and differing detector acceptance, to produce data-driven estimates for the FD ν_μ disappearance and ν_e appearance signals. This substantially reduces the impact of most uncertainties, particularly those in the neutrino beam and interaction cross section predictions. [16] Backgrounds in the ν_e candidate sample are constrained using the ND ν_e candidate spectra, which, assuming conventional 3-flavor oscillations, consist entirely of backgrounds; the same extrapolation procedure as for the ν_μ ND sample is applied to each subcomponent of the ν_e background after correction with the ND data. Backgrounds in the ν_μ candidate sample are small and simulated directly. Cosmogenic backgrounds in the FD are measured directly using data sampled in between NuMI pulses.

The oscillation parameters are determined from the observed FD ν_e, $\bar{\nu}_e$, $\bar{\nu}_\mu$, and ν_μ candidate spectra, using a binned Poisson likelihood fit in which various modeling parameters are also allowed to vary within their systematic uncertainties. The solar parameters θ_{12} and Δm^2_{21} as well as the angle θ_{13} are constrained using external measurements[17]. Frequentist one-dimensional exclusion profiles and two-dimensional surfaces are determined using the unified approach of Feldman & Cousins[18;19]. The large number of pseudoexperiments involved in the Feldman-Cousins procedure necessitates the use of specialized computing resources; recent results have employed supercomputers at NERSC[20].

Present measurements by NOvA indicate mild preferences for $\Delta m^2_{32} > 0$ (normal hierarchy) at 1.0σ confidence and $\sin^2\theta_{23} > 0.5$ (upper octant) at 1.2σ. The atmospheric parameters themselves are measured with good precision: Δm^2_{32} at 2.9%, and θ_{23} at 7.0%. No strong asymmetry in the rate of appearance of ν_e and $\bar{\nu}_e$ is observed, which results in exclusion of the (inverted hierarchy, $\delta_{CP} = \pi/2$) combination at more than 3σ confidence and disfavoring of (normal hierarchy, $\delta_{CP} = 3\pi/2$) with about 2σ confidence. However, any value of δ_{CP} may be compatible with the data given appropriate choices of hierarchy and octant; thus the current data do not favor any statement about CP conservation or violation.

4 Future 3-flavor oscillation sensitivity

NOvA is expected to run until 2025. This additional running time, together with the staged improvements to the beam that have already begun, stand to result in an additional factor of 2.5 in analyzed exposure. The total exposure will amount to 63×10^{20} POT, divided equally between neutrino and antineutrino beams. At the final exposure, systematic uncertainties are expected to have approximately the same impact on the measurements of the atmospheric parameters as the statistical uncertainties, and while a reduction in the systematic uncertainty budget is not included in the analysis presented here, some decreases are anticipated. The most significant systematics are related to the detector energy scale, which the current NOvA test beam program at Fermilab is anticipated to substantially reduce. Other important systematics from neutron propagation and neutrino interactions are being continually revised by measurements within NOvA and the incorporation of new external measurements and theoretical developments. Past successes in reducing similar systematics give reason for optimism that these may also be further constrained in the future.

In addition to improvements in the precision of the atmospheric parameter measurements, if the current analysis techniques and uncertainty budget are projected to the final exposure, NOvA has the potential to achieve important milestones in sensitivity to neutrino oscillations. NOvA would expect to resolve the mass hierarchy at $4-5\sigma$ sensitivity for certain parameter combinations such as (normal hierarchy, upper octant, $\delta_{CP} = 3\pi/2$) or (inverted hierarchy, upper octant, $\delta_{CP} = \pi/2$), meaning that these scenarios should be measured or ruled out with strong confidence by the end of NOvA's run. In addition, NOvA measurement sensitivity includes 95% confidence level determinations of the mass hierarchy for 45-60% of the possible values of δ_{CP} (depending on the true value of θ_{23}), as well as 2σ indications of CP violation for 20-30% of the δ_{CP} range.

Measurements of all three of the parameters are currently limited by their statistical precision, both in NOvA and in other experiments, such as T2K[21]. In particular, no consensus has yet emerged on the sign of Δm^2_{32} or the octant of θ_{23}, nor whether CP is violated in neutrinos. Mild tension between the preferred oscillation parameters of NOvA and T2K, however, may result in conclusions different than either experiment's findings alone when they are combined using a standard 3-flavor oscillation model[22;23]. This tension also admits explanations beyond the standard oscillation paradigm[24;25]. In either the case of new physics manifesting as non-L/E-dependent phenomena or the standard 3-flavor oscillation model over much of the parameter space, precision measurements at multiple neutrino energies and baselines are essential for disentangling the degeneracies that are otherwise present.

No other planned experiment will probe neutrino flavor change phenomena at a baseline near 810km. NOvA's remaining program provides a unique and irreplaceable opportunity to explore the intermediate baseline regime between that of the future T2HK and DUNE experiments.

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