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The NOvA Experiment and Exotic Neutrino Oscillations

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■ (NF2) Sterile neutrinos
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☐ (NF7) Applications
☐ (TF11) Theory of neutrino physics
■ (NF9) Artificial neutrino sources
■ (NF10) Neutrino detectors
☐ (Other) *[Please specify frontier/topical group(s)]*

Abstract

The majority of neutrino oscillation experiments have obtained evidence for neutrino oscillations that are compatible with the three-flavor model. Explaining anomalous results from short-baseline experiments, such as LSND and MiniBooNE, in terms of neutrino oscillations requires the existence of sterile neutrinos or other exotic beyond standard model explanations. The search for sterile neutrino mixing conducted in NOvA uses an 810 km baseline and two detectors; the Near Detector (ND) at Fermilab and the Far Detector (FD) in Minnesota. The signal for sterile neutrino oscillations is a deficit of neutral-current neutrino interactions at the FD with respect to the ND prediction. In this note we briefly describe the current analyses and results of searches for sterile neutrino oscillations on NOvA and non-standard interactions, and potential future projections.

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1 Introduction

The standard neutrino paradigm contains three neutrino mass eigenstates and one CP-violating phase. However, conflicting evidence has been presented on the issue of neutrino mixing between the three known active neutrinos and light sterile neutrino species. Apparent short-baseline neutrino appearance observed by the LSND[1] and MiniBooNE[2;3] experiments and the gallium anomaly[4;5] can be interpreted by the addition of sterile neutrinos with masses at the 1 eV^2 scale. Several other short-baseline and long-baseline searches have found no evidence for these light ν_s states and place strong constraints on their existence[6–13]. Additionally, differences between neutrino and antineutrino oscillation parameters inconsistent with the standard CPV and matter effects could manifest new physics involving interactions beyond the Standard Model (BSM), called non-standard interactions (NSI)[14], that modify the three-flavor disappearance probability.

2 The NOvA Experiment

NOvA is an 810 km baseline neutrino oscillation experiment whose neutrinos are sampled from the NuMI beam, produced at Fermilab in the Chicago suburbs. Neutrinos are observed at two locations by the experiment: at the Near Detector (ND), 100 m underground at Fermilab; and the Far Detector (FD), located on the surface in Ash River, Minnesota. Measurements in the 300 ton ND are used to constrain uncertainties in the beam flux and neutrino interaction models that are used to compute predictions at the 14 kton FD.

3 Measurements of exotic neutrino oscillations in NOvA

In the 3-flavor mixing framework, the rate of neutral current (NC) interactions is independent of neutrino flavor and is thus unaffected by oscillations. A deficit in the NC energy spectrum would be observed in the presence of a sterile neutrino, with a mass at the 0.1 to 10 eV^2 scale. For this scenario, the simplest extension is a 3+1 model that introduces a single new mass state ν_4 with a new sterile flavor state. In addition to the 3-flavor mixing parameters and the new mass splitting Δm^2_{41}, this model adds three new mixing angles θ_{14}, θ_{24} and θ_{34}, and two additional CP-violating phases δ_{14} and δ_{24}. The disappearance of NC events is sensitive to the 3+1 parameters θ_{24}, θ_{34}, δ_{24} and Δm^2_{41}. The value of Δm^2_{41} determines the frequency of the oscillations.

NOvA is sensitive to potential sterile neutrino mass splittings through analysis of NC events, specifically searching for a deficit of those events compared to expectation in both detectors for both neutrino and antineutrino beams. For sufficiently small values of the mass splitting, the oscillations develop over longer baselines than the ND and are more rapid than can be resolved at the FD, resulting in an average reduction in the NC rate at the FD relative to the ND. As the mass splitting increases, oscillations develop over shorter baselines and are evident at the ND. To date, NOvA sterile mixing analyses have considered oscillations driven by mass splittings in the range $0.05\ eV^2 < \Delta m^2_{41} < 0.5\ eV^2$, where the oscillations to a sterile neutrino are not rapid enough to appear at the ND.

NOvA selects candidate NC events interacting in the detectors using a machine learning classifier called CVN[15], that efficiently discriminates between NC interactions, backgrounds from charged-current (CC) interactions, and cosmic-ray backgrounds in the FD. The predicted FD spectrum is produced following a data-driven approach in which the ND data is used to constrain the simulation before extrapolating the resulting distribution to the FD. The effects of oscillations are applied by using simulation to infer the flavor composition and neutrino energy. This approach is powerful in partially cancelling any correlated uncertainties between the two detectors, but results in sensitivity only to active-to-sterile oscillations which develop over larger distances than the ND baseline.

The set of oscillation parameters that are most consistent with the observed FD data are determined by joint fits to the NC candidate spectra, where the oscillation parameters and numerous systematic degrees of freedom are allowed to vary. The best fits are obtained by minimizing a binned Poisson likelihood over all of the spectra simultaneously. One-dimensional exclusion profiles and two-dimensional surfaces are determined using the Feldman-Cousins Unified Method [16;17]. The large number of pseudo-experiments involved in the Feldman-Cousins procedure necessitates the use of specialized computing resources; recent results have employed supercomputers at NERSC [18].

NOvA has analyzed 8.85×10^{20} protons-on-target (POT) of neutrino data in the NC disappearance channel (of the total 13.6×10^{20} POT recorded). The analysis observes 214 neutral-current candidates at the far detector compared with a prediction of $191.2 \pm 13.8\ (stat.) \pm 22.0\ (syst.)$ assuming standard three-flavor mixing. No depletion of NC events was observed. In the range $0.05\ eV^2 < \Delta m^2_{41} < 0.5\ eV^2$, limits of $\theta_{24} < 16.2°$ and $\theta_{34} < 29.8°$ are obtained at the 90% confidence level [19;20]. Additionally, with a very pure antineutrino beam, NOvA has recorded and analyzed a beam exposure of 12.5×10^{20} protons-on-target (POT) of antineutrino data. A total of 121 NC-candidate events were observed, consistent with expectations from 3-flavor oscillations of $122 \pm 11\ (stat.) \pm 18\ (syst.)$. $\theta_{24} < 24.7°$ and $\theta_{34} < 31.7°$ obtained at the 90% confidence level [21].

4 Future sensitivity of NOvA

NOvA is implementing a hybrid fitting technique which combines a Gaussian multivariate treatment of systematic uncertainties with a Poisson likelihood ratio treatment of statistical uncertainties. This method accounts for correlations in systematic uncertainties between multiple detectors, and provides a correct treatment of statistical uncertainties at low statistics. The methodology encodes the modified energy spectra for all possible systematic uncertainties in a covariance matrix spanning the energy bins in both detectors thus enabling the analysis to set limits on the mixing parameters $\sin^2\theta_{24}$ and $\sin^2\theta_{34}$ for values of the sterile neutrino mass-splitting $\Delta m^2_{41} > 10^{-4}$ eV^2 and incorporates oscillations at the ND baseline.

NOvA has been approved to run until 2025, which together with the staged improvements to the beam that have begun, are expected to result in an additional factor of 2.5 in analyzed exposure. A total exposure of 63×10^{20} POT is targeted, to be divided roughly equally between neutrino and antineutrino beams. In addition to the covariance matrix fitting procedure, NOvA will also include the ν_μ CC disappearance channel as a further constraint on θ_{23} and on the systematic uncertainty for background estimation. A joint fit of the two neutrino beam modes will also be included in future analyses. At full exposure, NOvA should provide the most sensitive analysis of sterile oscillation parameters for long-baseline experiments. The projected sensitivity would exclude values of $\Delta m^2_{41} > 0.5$ eV^2 and $\sin^2\theta_{24} < 0.01$ at the 90% C.L. These improvements are projected to extend the region of phase space currently excluded by MINOS, MINOS+, Daya Bay, Bugey-3 [13].

NOvA also has mature analyses exploring NSI and projects competitive constraints compared to MINOS NSI [22] searches. Particularly, NOvA is studying constraints on the NSI parameter $\epsilon_{\mu\tau}$ that gives the strength of the NSI effect on transitions between μ and τ flavors, by analysing the 3-flavor ν_μ CC disappearance channel with an NSI extension. Furthermore, the ν_e CC disappearance channel jointly fit with ν_μ CC has sensitivity to the NSI parameters ϵ_μ and ϵ_τ and is currently under investigation.

In closing, the NOvA experiment provides a unique opportunity to explore flavor change phenomena with ~ 2 GeV neutrinos at a baseline of 810 km, which could be a critical part of understanding any non-L/E-dependent new physics.

References

[1] A. Aguilar et al. (LSND), Physical Review D **64** (2001), 10.1103/PhysRevD.64.112007.

[2] A. A. Aguilar-Arevalo et al. (MiniBooNE), Physical Review Letters **110** (2013), 10.1103/physrevlett.110.161801.

[3] A. A. Aguilar-Arevalo et al. (MiniBooNE), "Updated miniboone neutrino oscillation results with increased data and new background studies," (2020), arXiv:2006.16883 [hep-ex] .

[4] M. A. Acero, C. Giunti, and M. Laveder, Phys. Rev. D **78**, 073009 (2008).

[5] C. Giunti and M. Laveder, Phys. Rev. C **83**, 065504 (2011).

[6] P. Adamson et al. (Daya Bay and MINOS), Phys. Rev. Lett. **117**, 151801 (2016).

[7] P. Adamson et al. (MINOS), Phys. Rev. Lett. **117**, 151803 (2016).

[8] F. P. An et al. (Daya Bay), Phys. Rev. Lett. **115**, 111802 (2015).

[9] K. Abe et al. (Super-Kamiokande), Phys. Rev. D **91**, 052019 (2015).

[10] M. G. Aartsen et al. (IceCube), Phys. Rev. Lett. **117**, 071801 (2016).

[11] M. Aartsen et al. (IceCube), (2020), arXiv:2005.12942 [hep-ex] .

[12] M. Aartsen et al. (IceCube), (2020), arXiv:2005.12943 [hep-ex] .

[13] P. Adamson, F. P. An, et al. (Daya Bay and MINOS+), Phys. Rev. Lett. **125**, 071801 (2020).

[14] Neutrino Non-Standard Interactions: A Status Report, Vol. 2 (2019) arXiv:1907.00991 [hep-ph] .

[15] A. Aurisano, A. Radovic, D. Rocco, A. Himmel, M. D. Messier, E. Niner, G. Pawloski, F. Psihas, A. Sousa, and P. Vahle, JINST **11**, P09001 (2016), arXiv:1604.01444 [hep-ex] .

[16] G. J. Feldman and R. D. Cousins, Phys. Rev. **D57**, 3873 (1998), arXiv:physics/9711021 [physics.data-an] .

[17] A. Sousa, N. Buchanan, S. Calvez, P. Ding, D. Doyle, A. Himmel, B. Holzman, J. Kowalkowski, A. Norman, and T. Peterka, in Proceedings of the 23rd International Conference on Computing in High-Energy and Nuclear Physics (2019) in press.

[18] `https://www.nersc.gov/`, the National Energy Research Scientific Computing Center, a U.S. Department of Energy Office of Science User Facility.

[19] P. Adamson et al. (NOvA), Phys. Rev. D **96**, 072006 (2017).

[20] G. S. Davies (NOvA), PoS **NuFact2017**, 006 (2018).

[21] M. Wallbank, "First active to sterile neutrino search from NOvA using the antineutrino beam," `https://nova-docdb.fnal.gov/cgi-bin/private/ShowDocument?docid=47203` (2019), Fermilab JETP seminar, October 18 2019.

[22] P. Adamson et al. (MINOS), Phys. Rev. D **88**, 072011 (2013).