ELEMENTARY PARTICLES AND FIELDS

Experiment

Study of Neutrino Oscillations in the NOvA Experiment

L. D. Kolupaeva^{1)*} and O. B. Samoylov^{1)**}

Received July 23, 2020; revised July 23, 2020; accepted July 23, 2020

Abstract—NOvA is a neutrino experiment deployed at Fermi National Accelerator Laboratory (FNAL, USA) and designed for studying oscillations—namely, the appearance of electron neutrinos and the survival of muon neutrinos. Two detectors, a near and a far one, are separated by a distance of 810 km and are positioned at an angle of 14 mrad with respect to the axis of a beam from the NuMI accelerator complex. This configuration provides an optimum relationship between the energy and distance for neutrino oscillations. The experiment is aimed at measuring the neutrino mass hierarchy, determining the phase of CP violation in the lepton sector, and refining value of the parameters θ_{23} and Δm_{32}^2 , as well as at performing some other tasks. The results of the NOvA analysis performed jointly for a 8.85×10^{20} proton-on-target (POT) neutrino beam and a 12.33×10^{20} POT antineutrino beams are discussed. Also, further prospects of the experiment are outlined.

DOI: 10.1134/S1063778821010117

1. INTRODUCTION

The NOvA long-baseline accelerator neutrino experiment [1] is devoted to studying neutrino oscillations. It employs near and far detectors that are two identical tracking calorimeters. The NuMI accelerator is used to create a directed beam of muon (anti)neutrinos [2]. Interacting with a carbon target, a proton beam produces predominantly (anti)neutrinos of muon flavor. The emerging flow travels a distance of 810 km through the Earth's crust toward the far detector of the experiment. The far detector is positioned in the Minnesota state on the border with Canada.

The results published most recently [3] are based on an analysis of data from detectors exposed to a 8.85×10^{20} proton-on-target (POT) neutrino beam and a 12.33×10^{20} POT antineutrino beam. These data were collected from February 2014 to February 2019. The rated power of the experiment is 700 kW; this implies 6×10^{20} protons dumped to the target (POT) per year of accelerator operation. The mode of the neutrino–antineutrino beam used is determined by the field of magnetic horns focusing secondary mesons of the required electric charge after the target.

The detectors of the experiment were designed in such a way as to record electron and muon neutrinos. They are placed at an angle of 14.6 mrad with respect to the beam axis. This makes it possible to

obtain a narrow monochromatic peak at an energy of about 2 GeV. The near detector has geometric dimensions of $4.2 \times 4.2 \times 16$ m and a mass of about 300 t. It is located at a distance of 1 km downstream of the target and is used to measure the neutrino-beam composition before oscillations. The far detector has substantially larger dimensions ($15.6 \times 15.6 \times 60$ m) and a substantially higher mass (14 kt). The two detectors have an identical structure and consist of a large number of PVC cells [4] of cross-sectional area 3.9×6.6 cm filled with a liquid scintillator [5] from a mixture of mineral oil and pseudocumene. In each cell, there is a loop formed by a wavelength-shifting optical fiber and connected to a 32-channel avalanche photodiode. In order to accomplish a three-dimensional reconstruction of events, the detector is manufactured from alternating horizontal and vertical planes of cells. The flavor of a neutrino that is recorded in the detector is determined by means of a convolutional neural network implementing the Convolutional Visual Network (CVN) algorithm [6]. The identical near and far detectors make it possible to employ an event-extrapolation procedure that supplements a Monte Carlo simulation of events. This permits realistically predicting the composition of the beam in the far detector and substantially reducing systematic uncertainties.

The spectrum of electron- and muon-neutrino events in the far detector is sensitive to specific oscillation parameters including the atmospheric difference of the squared masses, Δm_{32}^2 ; the mixing

¹⁾Joint Institute for Nuclear Research, Dubna, Russia.

*E-mail: ldkolupaeva@yandex.ru

**E-mail: samoylov@jinr.ru

Fig. 1. Reconstructed-energy spectrum of events selected in the far detector of the NOvA experiment. Also shown in the panels are the predictions of a Monte Carlo simulation for the best fit with an extrapolation from the near to the far detector. Muon-neutrino and muon-antineutrino (ν_μ and $\bar{\nu}_\mu$, respectively) events were selected into quartiles according to the reconstructed hadron energy [7].

angle, θ_{23} ; the CP -violation phase in the lepton sector, δ_{CP} ; and the neutrino mass hierarchy.

2. RESULTS OF DATA ANALYSIS WITH STATISTICS OF 2019

In the far detector, 58 events in the $\nu_\mu \rightarrow \nu_e$ channel (the predicted background is 15.0), 27 events in the $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ channel (the predicted background is 10.3), 113 events in the $\nu_\mu \rightarrow \nu_\mu$ channel (the predicted background is 4.2), and 102 events in the $\bar{\nu}_\mu \rightarrow \bar{\nu}_\mu$ channel (the predicted background is 2.2) were found over the whole period of data acquisition. The number of detected $\bar{\nu}_e$ events is 4.4σ , which is indicative of the appearance of $\bar{\nu}_e$ in the $\bar{\nu}_\mu$ beam. The measured spectra of events are shown in Fig. 1. For more details of event selection and the subsequent analysis, the interested reader is referred to [7].

A joint fit to the measured spectra of ν_μ , $\bar{\nu}_\mu$, ν_e , and $\bar{\nu}_e$ candidate events led to the following conclusions

on the oscillation parameters. The best fitted values are the following: $\Delta m_{32}^2 = 2.48^{+0.11}_{-0.06} \times 10^{-3} \text{ eV}^2$, $\sin^2 \theta_{23} = 0.56^{+0.04}_{-0.03}$, and $\delta_{CP} = 0.0^{+1.3}_{-0.4} \pi$. This corresponds to a normal mass hierarchy and to the upper octant of θ_{23} ($> \pi/4$). The 1, 2, and 3σ fiducial-level contours are shown in Fig. 2. An inverted mass hierarchy is disfavored at a level of 1.9σ , while the lower octant of θ_{23} is disfavored at a level of 1.6σ , but the result is still in agreement with the maximal mixing angle of θ_{23} at a level of 1.2σ . A large region of inverted mass hierarchy around $\delta_{CP} = \pi/2$ is disfavored at a level higher than 3σ . All values of δ_{CP} are resolved at a level of 1.1σ for a normal mass hierarchy and the upper octant of θ_{23} .

3. PROSPECTS OF THE NOvA EXPERIMENT

In addition to accumulating vaster statistics for analysis, the NOvA experiment improves its own

Fig. 2. Contours of 1, 2, and 3σ fiducial levels for the $\sin^2\theta_{23}$ – δ_{CP} plane and significance at which various values of δ_{CP} and θ_{23} are disfavored.

means for data processing. Changes in various stages of the Monte Carlo simulation of events is expected in the near future [8]. They will include refining models of the cross section for neutrino interaction with a detector material [9, 10] and the response of the scintillator to particle propagation [11, 12] and improving detector calibrations. A test beam for a smaller scale test-beam detector functionally identical to the near and far detectors was created at Fermilab [13]. It will permit obtaining deeper insight into the operation of all detector components and the detector response to a pure beams of probing particles. This is of importance for understanding the topology of such particles in the detector, and the results of this are applicable in the training of neural networks for the recognition of these particles. Event reconstruction is also improved, and neural networks are used more widely for this [14, 15]. The data analysis techniques and statistical methods are also modified.

The NOvA experiment is planned to be continued up to 2025 until the shutdown of the accelerator for the final stages of the DUNE experiment [16]. A gradual rise in the power of the accelerator is intended over these years in accordance with the PIP-II plan [17]. All this would permit NOvA to accumulate

36×10^{20} POT for the neutrino beam and 36×10^{20} POT for the antineutrino beam.

The expected resolutions in the neutrino mass hierarchy and in the CP -violation phase δ_{CP} are shown in Fig. 3. To the end of data accumulation, NOvA would in principle be able to measure the mass hierarchy at a level of 0.5 to 5σ, depending on the values that the oscillation parameters do indeed assume in nature. At the present time, global analyses of data from neutrino experiments favor a normal mass hierarchy and $\delta_{CP} \approx 3\pi/2$ [18]. For these values, the sensitivity of NOvA to the mass hierarchy and δ_{CP} may reach maximally about 5σ and 2σ, respectively.

In addition to individual measurements, the T2K and NOvA experiments are going to perform a simultaneous analysis of their data [19]. This would make it possible to improve constraints on the oscillation parameters and would become the first joint work of two oscillation experiments.

At the end of the first decade of XXI century, neutrino experiments had reached the phase of precision measurements, but, at the present time, there remain unexplored facets of neutrino oscillations. In the next decade, large detectors and powerful particle sources will be created in order to fill these gaps.

Fig. 3. Mass-hierarchy and δ_{CP} resolutions expected to be reached by NOvA in 2025 with the total statistics of $36 \times 10^{20}(\nu) + 36 \times 10^{20}(\bar{\nu}_e)$ POT. The lower panels show the resolutions with allowance for the current best value from the fit to the NOvA data.

ACKNOWLEDGMENTS

We are grateful to A.G. Olshevsky, head of the NOvA project at Joint Institute for Nuclear Research (JINR, Dubna) for stimulating discussions.

FUNDING

This study was supported in part by Russian Science Foundation (project no. 18-12-00271) and Russian Foundation for Basic Research (project no. 19-32-90058).

REFERENCES

1. NOvA Collab. (D. S. Ayres et al.), hep-ex/0503053.
2. NOvA Collab. (P. Adamson et al.), Nucl. Instrum. Methods Phys. Res., Sect. A **806**, 279 (2016); arXiv: 1507.06690 [physics.acc-ph].
<https://doi.org/10.1016/j.nima.2015.08.063>
3. NOvA Collab. (M. A. Acero et al.), Phys. Rev. Lett. **123**, 151803 (2019); arXiv: 1906.04907 [hep-ex].
<https://doi.org/10.1103/PhysRevLett.123.151803>
4. R. L. Talaga, J. J. Grudzinski, S. Phan-Budd, A. Pla-Dalmau, J. E. Fagan, C. Grozis, and K. M. Kephart, Nucl. Instrum. Methods Phys. Res., Sect. A **861**, 77 (2017); arXiv: 1601.00908 [physics.ins-det].
<https://doi.org/10.1016/j.nima.2017.03.004>
5. S. Mufson, B. Baugh, C. Bower, T. E. Coan, J. Cooper, L. Corwin, J. A. Karty, P. Mason, M. D. Messier, A. Pla-Dalmau, and M. Proudfoot, Nucl. Instrum. Methods Phys. Res., Sect. A **799**, 1 (2015); arXiv: 1504.04035 [physics.ins-det].
<https://doi.org/10.1016/j.nima.2015.07.026>
6. A. Aurisano, A. Radovic, D. Rocco, A. Himmel, M. D. Messier, E. Niner, G. Pawloski, F. Psihas, A. Sousa, and P. Vahle, J. Instrum. **11**, P09001 (2016); arXiv: 1604.01444 [hep-ex].
<https://doi.org/10.1088/1748-0221/11/09/P09001>
7. NOvA Collab. (M. A. Acero et al.), Phys. Rev. D **98**, 032012 (2018); arXiv: 1806.00096 [hep-ex].
<https://doi.org/10.1103/PhysRevD.98.032012>
8. A. Aurisano, C. Backhouse, R. Hatcher, N. Mayer, J. Musser, R. Patterson, R. Schroeter, and A. Sousa, J. Phys.: Conf. Ser. **664**, 072002 (2015).
<https://doi.org/10.1088/1742-6596/664/7/072002>

9. I. D. Kakorin, K. S. Kuzmin, and V. A. Naumov, Phys. Part. Nucl. Lett. **17**, 265 (2020).
<http://theor.jinr.ru/NeutrinoOscillations/Papers/PEPANL2020.pdf>.
10. J. Wolcott (for the NOvA Collab.), PoS (NuFACT2018) 098 (2018); arXiv:1812.05653 [hep-ex].
<https://doi.org/10.22323/1.341.0098>
11. O. B. Samoylov, N. V. Anfimov, A. I. Antoshkin, and A. P. Sotnikov, in *Proceedings of the 27th International Symposium Nuclear Electronics and Computing (NEC'2019), Budva, Becici, Montenegro, Sept. 30–Oct. 4, 2019*.
<http://ceur-ws.org/Vol-2507/439-442-paper-81.pdf>.
12. S. Yu, arXiv: 1910.07035 [physics.ins-det].
13. A. Sutton (on behalf of the NOvA Collab.), PoS (NuFACT2018) 058 (2018).
<https://doi.org/10.22323/1.341.0058>
14. F. Psihas, E. Niner, M. Groh, R. Murphy, A. Aurisano, A. Himmel, K. Lang, M. D. Messier, A. Radovic, and A. Sousa, Phys. Rev. D **100**, 073005 (2019); arXiv: 1906.00713 [physics.ins-det].
<https://doi.org/10.1103/PhysRevD.100.073005>
15. P. Baldi, J. Bian, L. Hertel, and L. Li, Phys. Rev. D **99**, 012011 (2019); arXiv: 1811.04557 [physics.ins-det].
<https://doi.org/10.1103/PhysRevD.99.012011>
16. DUNE Collab. (B. Abi et al.), arXiv: 2002.02967 [physics.insdet].
17. V. Lebedev (PIP-II Collab.), The PIP-II Reference Design Report.
<https://doi.org/10.2172/1365571>
18. I. Esteban, M. C. Gonzalez-Garcia, A. Hernandez-Cabezudo, M. Maltoni, and T. Schwetz, J. High Energy Phys. **1901**, 106 (2019); arXiv: 1811.05487 [hep-ph].
[https://doi.org/10.1007/JHEP01\(2019\)106](https://doi.org/10.1007/JHEP01(2019)106)
19. T2K and NOvA Collaborations to Produce Joint Neutrino Oscillation Analysis (2018).
<https://t2k-experiment.org/2018/01/t2k-nova-announce/>.