Measurement of the neutrino oscillation parameters by NOvA

M A Acero

1 Programa de Física, Universidad del Atlántico, Puerto Colombia, Colombia

E-mail: marioacero@mail.uniatlantico.edu.co

Abstract. Using a beam made (mainly) by muon neutrinos traveling through the earth, the NOvA Experiment looks for the appearance of electron neutrinos, a transformation explained by the quantum-mechanical phenomenon known as neutrino oscillation. NOvA uses two neutrino detectors located 14.6 mrad off-axis from the main beam direction. The first (Near) detector stands at a distance of 1 km from the neutrino source, while the second (Far) one is at 810 km. Traveling from the Near Detector to the Far Detector, muon neutrinos can morph into electron neutrinos with a probability depending upon the parameters $\Delta m^2_{32}$ and $\sin^2 \theta_{23}$, among others. By comparing the observed number of $\nu_\mu$ and $\nu_e$ events at the Far Detector with the expected number of events predicted by a 3-neutrino oscillation model, NOvA is able to measure these parameters and help to improve our understanding about neutrinos. After a brief introduction to the physics of neutrinos and a presentation of the experiment, in this talk the most recent results obtained by NOvA through the study of muon neutrino oscillations $\nu_\mu \rightarrow \nu_\mu$ and $\nu_\mu \rightarrow \nu_e$, are shown. The oscillation parameters are found to be $\Delta m^2_{32} = 2.44 \times 10^{-3}$ eV$^2$ and $\sin^2 \theta_{23} = 0.56$.

1. Introduction

Neutrinos are elementary particles characterized by having no electric charge and 1/2-spin. As part of the Standard Model (SM) of particle physics, they are the neutral companions of the charged leptons, so making a group of three neutrinos (flavor states): $\nu_e, \nu_\mu, \nu_\tau$. They interact only through the weak interaction, mediated by the $W^\pm$ and $Z$ bosons, and are assumed to be massless in the SM (see, for instance, [1]).

Experimentally it has been established that neutrinos are able to change its flavor, a phenomenon known as neutrino oscillation, implying that, contrary to what the SM states, neutrinos are massive particles and states with definite flavor ($\nu_e, \nu_\mu, \nu_\tau$) are a mixture of neutrinos with definite mass ($\nu_1, \nu_2, \nu_3$). Models of neutrino masses and mixing, and its implications on physics beyond the SM have been studied widely studied [2–6], looking for an understanding of neutrino physics and its phenomenology.

Neutrino mixing is usually parametrized as

$$
\begin{pmatrix}
\nu_e \\
\nu_\mu \\
\nu_\tau
\end{pmatrix} = R(\theta_{23}) \cdot R(\theta_{13}, \delta_{CP}) \cdot R(\theta_{12})
\begin{pmatrix}
\nu_1 \\
\nu_2 \\
\nu_3
\end{pmatrix};
$$

(1)

$R(\theta_{ij})$ in Equation (1) are the orthogonal rotation $3 \times 3$ matrices presented in Equation (2):
\[
R(\theta_{12}) = \begin{pmatrix}
c_{12} & s_{12} & 0 \\
-s_{12} & c_{12} & 0 \\
0 & 0 & 1
\end{pmatrix}, \quad R(\theta_{23}) = \begin{pmatrix}
1 & 0 & 0 \\
0 & c_{23} & s_{23} \\
0 & -s_{23} & c_{23}
\end{pmatrix}, \quad R(\theta_{13}) = \begin{pmatrix}
c_{13} & 0 & s_{13}e^{-i\delta_{CP}} \\
0 & 0 & 1 \\
-s_{13}e^{i\delta_{CP}} & c_{13} & 0
\end{pmatrix}
\]

where \(s_{ij} \equiv \sin \theta_{ij}, \ c_{ij} \equiv \cos \theta_{ij}\), and \(\delta_{CP}\) is a phase which parametrizes the CP violation in the lepton sector.

This parametrization, and using the basics of quantum mechanics to compute the transition between neutrinos of different flavor, allows to find the probability that a neutrino created at the source with a flavor \(\alpha\) is observed at the detector as a neutrino with flavor \(\beta\) after traveling a given distance \(L\):

\[
P_{\nu_\alpha \rightarrow \nu_\beta} = |\langle \nu_\beta | \nu_\alpha(L) \rangle|^2 = \left| \sum_k U_{\beta k}^* \exp \left( -i \frac{m_{2k}^2 L}{2E} \right) U_{\alpha k} \right|^2
\]

From the probability in Equation (3), it is clear that if neutrinos are massive, the oscillation probability is not null. Equation (3) also shows that the flavor transition depends on \(\Delta m_{ij}^2 \equiv m_i^2 - m_j^2\) and not on the neutrino mass itself, indicating that this phenomenon would not give information about the absolute neutrino masses.

The mixing angles and the squared-mass differences have been precisely measured by experiments using neutrinos from the sun (\(\theta_{12}, \Delta m_{12}^2\)), reactors (\(\theta_{13}\)) and the atmosphere and accelerators (\(\theta_{23}, \Delta m_{32}^2\)) (global neutrino-oscillation data analyses combining all available data can be found in \([7,8]\)).

2. The NOvA experiment

The NOvA (NuMI Off-axis \(\nu_e\) Appearance) Collaboration brings together a group of around 250 scientists (professors, researchers, students) and engineers from 49 institutions across 7 countries. The NOvA experiment \([9-11]\) is a two-detector long-baseline neutrino oscillation experiment looking for the appearance of (anti-)electron neutrinos from a beam of (anti-)muon neutrinos. Its main scientific goals include the search for answering the questions about the neutrino mass ordering, the measurement of CP-violating phase and the measurement of \(\theta_{23}\), by studying neutrino oscillations using the four channels depicted in Equation (4):

\[
\begin{align*}
\nu_\mu & \rightarrow \nu_\mu, \\
\nu_\mu & \rightarrow \nu_e, \\
\bar{\nu}_\mu & \rightarrow \bar{\nu}_\mu, \\
\bar{\nu}_\mu & \rightarrow \bar{\nu}_e
\end{align*}
\]

The neutrino beam, which can be operated in either a neutrino or antineutrino mode, is created following the decay of charged pions to (anti-)muons and (anti-)neutrinos. In the neutrino mode, the whole chain results in a beam composed mainly by \(\nu_\mu s\) (95%), with a small contamination of \(\nu_e s\) (1%) and \(\bar{\nu}_\mu s\) (4%). The energy spectrum of the beam as expected at the FD, separated by its composition is shown in Figure 1.

The NOvA neutrino detectors are functionally identical calorimeters consisting of cells filled with a liquid scintillator, organized in planes alternating in vertical and horizontal orientations. Events taking place in the cells may produce light which is collected by an optical fiber connected to an avalanche photodiode. The alternation of horizontal and vertical planes allows NOvA to have top and side views for each event as particle crossing different cells are detected by the energy deposited in them. In this way, it is possible to reconstruct the particle trajectory by following the created track up to the point where the event was originated (interaction point).
Thanks to the granularity of the detectors, the tracks left by the interacting particles (coming from the beam and cosmic rays) have been used by NOvA to implement an event selection and classification process based on image recognition techniques known as Convolutional Visual Network (CVN) [12]. This method is based on training a series of linear operations using simulated events, in order to extract their features to identify the topology of specific interaction, with special focus on neutrino-like events.

The Far Detector (FD) is made by 896 planes, with a total mass of 14 kt. It is placed near Ash River, Minnesota, at 810 km from the neutrino source, at Fermilab, and at an angle of 14.6 mrad from the central axis of the neutrino beam, resulting in a neutrino flux with a narrow band energy distribution and peaked around 1.9 GeV (see Figure 2).

The Near Detector (ND), on the other hand, consists of 214 planes with a mass of 290 ton, and is located at Fermilab, 100 m underground (to reduce background from cosmic cays) and 1 km away from the neutrino source. Its position is such that the angle with respect to the main beam axis is the same as the FD, in order to obtain a similar neutrino energy spectrum to the one expected at the FD in the absence of oscillations.
3. Data analysis and results

3.1. Disappearance and appearance data

The results presented here were obtained by NOvA using data collected from February 2014 to February 2017, for a total of $8.85 \times 10^{20}$ protons on target [11]. As mentioned above, NOvA has the possibility to study the disappearance of $\nu_\mu$ or $\bar{\nu}_\mu$ and the appearance of $\nu_e$ or $\bar{\nu}_e$. Here, the results of the neutrino mode study are presented, and the measured values of the oscillation parameters from a joint (appearance-disappearance) analysis are reported.

Following a rigorous selection process (detailed description can be found in [11]), a total of 126 $\nu_\mu$ events were observed in the FD with an energy distribution as shown in Figure 3. The figure compares the data (black dots with error bars) against the expected number of events under the hypothesis of neutrino oscillation (purple solid line). In the absence of oscillations, we would have expected to observe $\sim 720$ muon neutrino events, a clear indication of $\nu_\mu$ disappearance.

The analysis performed by NOvA found that the most relevant region on the energy spectrum is around 1.6 GeV, where a sharp dip is observed. This is why the bin width is smaller in this part of the spectrum. A good (energy) location of the dip and its depth allows NOvA to get precise measurement of $\Delta m_{32}^2$ and $\sin^2 \theta_{23}$, respectively.

Regarding the appearance of electron neutrinos, a total of 66 $\nu_e$ events were observed, while only 7 were expected from the beam. In this case, a specific and distinctive classification of data was used in order to extract the most information from them, after applying the selection processes, including CVN, which tags events from a value ranging from 0 (less $\nu_e$-like event) to 1 (more $\nu_e$-like event). The resulting energy distribution of the data is shown in Figure 4. Again, data (black dots) are compared against the best fit of the neutrino oscillation model (purple solid line), and the expected background is also shown. Like for the case of $\nu_\mu$ disappearance, the prediction of neutrino oscillations is well in agreement with data, which is a clear indication of $\nu_e$s appearance from a beam mainly composed by $\nu_\mu$s.
3.2. Joint data fit

A simultaneous fit to the data from $\nu_\mu$ disappearance and $\nu_e$ appearance was performed by NOvA, including information about uncertainties from different sources (see details in [11]), in a suitable $\chi^2$ function to be minimized with respect to the oscillation parameters. For the analysis, the effect that matter has on the oscillation is also considered by using the CRUST2.0 model [13] of the Earth density with $\rho = 2.84\text{g/cm}^3$, taking into account the depth of the NuMI beam (810 km) for the NOvA baseline.

The best fit of the oscillation parameters is found to be

$$\Delta m^2_{32} = 2.44 \times 10^{-3}\text{eV}^2, \quad \sin^2 \theta_{23} = 0.56, \quad \delta_{\text{CP}} = 1.21\pi$$

(5)

The values in Equation (5) correspond to a normal mass ordering and the upper $\theta_{23}$ octant (i.e. $\theta_{23} > 45^{\circ}$), with $\chi^2 = 86.4/72$ DOF (Degrees of Freedom). The minimization of the $\chi^2$ function produce another local minimum close to the best fit (global minimum) also for normal mass ordering, but in the lower $\theta_{23}$ octant, with a difference of its $\chi^2$ and the overall best fit $\Delta \chi^2 = 0.13$. On the other hand, the inverted mass hierarchy case results being largely disfavored.

![Figure 5](image1.png)

**Figure 5.** Allowed regions of the $(\Delta m^2_{32}, \sin^2 \theta_{23})$ parameter space obtained from the joint analysis of $\nu_e$ appearance and $\nu_\mu$ disappearance data. Different color intensity corresponds to different levels of significance. Top: normal mass ordering; bottom: inverted ordering [11].

![Figure 6](image2.png)

**Figure 6.** Allowed regions of the $(\sin^2 \theta_{23}, \delta_{\text{CP}})$ parameter space obtained from the joint analysis of $\nu_e$ appearance and $\nu_\mu$ disappearance data. Different color intensity corresponds to different levels of significance. Top: normal mass ordering; bottom: inverted ordering [11].

Figure 5 and Figure 6 show the 2-dimensional contours at 1, 2 and 3$\sigma$ C.L. for the oscillation parameter spaces $(\Delta m^2_{32}, \sin^2 \theta_{23})$ and $(\sin^2 \theta_{23}, \delta_{\text{CP}})$, respectively. Upper plots correspond
to the normal mass ordering while bottom plots refer to inverted ordering. From them, 1-dimensional (1σ C.L.) allowed regions can be extracted for each parameter and the intervals are exhibited in Table 1 (for the normal mass ordering).

**Table 1.** 1σ confidence intervals for the oscillation parameters in the normal mass ordering [11].

| Parameter (units) | 1σ interval(s) |
|-------------------|----------------|
| $\Delta m_{32}^2 (10^{-3}\text{eV}^2)$ | [2.37, 2.52] |
| $\sin^2 \theta_{23}$ | [0.43, 0.51] and [0.52, 0.60] |
| $\delta_{CP} (\pi)$ | [0, 0.12] and [0.91, 2] |

Among other features, the contour plots show that the normal mass ordering is preferred over the inverted one; this is evident by the fact that the red contours (bottom plots) are smaller than the blue ones, and that the 1σ region is very small (Figure 5) or even absent (Figure 6). It is noticeable that a large region around $\delta_{CP} = \pi/2$ for the inverted ordering, Figure 6 bottom plot, is excluded at $> 3\sigma$ C.L. Notice also that $\theta_{23} = 45^\circ$ is excluded at a 0.8σ significance, which is different to what was reported previously by NOvA (2.6σ) [14]; this is given by the improvement of the event simulations and calibration, and also by the increased statistics.

Finally, Figure 7 shows a comparison of the results obtained by NOvA against other long-baseline experiments. The comparison is for the 90% C.L. allowed regions in the $(\Delta m_{32}^2, \sin^2 \theta_{23})$ parameter space for the normal mass ordering case. The plot nicely shows that all the experiments are consistent between each other and all of them are concordant with $\theta_{23} = 45^\circ$ i.e., maximal mixing.

![Figure 7. Comparison of the allowed regions of the $\Delta m_{32}^2$ vs. $\sin^2 \theta_{23}$ parameter space at the 90% C.L. obtained by different experiments: NOvA (black line; best-fit value, black point) [11], T2K [15] (green dashed), MINOS [16] (red dashed), IceCube [17] (blue dotted), and Super-Kamiokande [18] (purple dash-dotted).](image)

As mentioned in Section 2, the neutrino beam can be operated in an anti-neutrino mode, too. NOvA has already performed an analysis of anti-neutrino data, and the first results were presented at the XXVIII International Conference on Neutrino Physics and Astrophysics (Neutrino 2018, https://www.mpi-hd.mpg.de/nu2018/) [19], and will be published in an upcoming paper.
4. Conclusions

NOvA has clearly observed the disappearance of muon neutrinos and the appearance of electron neutrinos from a beam primarily made of $\nu_\mu$s. These observations are in good agreement with a three-neutrino oscillation model with the relevant parameters given in Equation (5), and allowed intervals as in Table 1. Data favor a normal mass ordering and an important region around $\delta_{CP} = \pi/2$ for the inverted ordering is excluded with a significance larger than 3$\sigma$; as a matter of fact, the inverted ordering is disfavored at the 95% C.L. overall. Finally, the NOvA results are consistent with maximal mixing in the $\mu - \tau$ sector, which is in concordance with other long-baseline neutrino oscillation experiments.

Acknowledgments

M.A.A. thanks the support given by Universidad del Atlántico through the Vicerrectoría de Investigaciones, Extensión y Proyección Social. The author also thanks to the Neutrino Physics Center (Fermilab) for the support provided through the “Neutrino Physics Center Fellowship” in the Spring 2016.

References

[1] Martínez R 2006 Las interacciones no gravitacionales Momento 32 28
[2] Moreno A, Quimbay C 2004 Mezcla de neutrinos y mecanismo See-Saw Momento 28 15
[3] Arrieta E, Nowakowski M 2006 Models of neutrino masses Revista Colombiana de Física 38 1210
[4] Cataño E, Martínez R 2009 Bariogénesis a través de Leptogénesis Momento 39 30
[5] Duarte J, Rodríguez J-Alexis and Martínez R 2009 Neutrinos en modelos 331 supersimétricos Revista Colombiana de Física 41 213
[6] King S 2015 Models of neutrino mass, mixing and CP violation J. Phys. G 42 123001 (Preprint arXiv:1510.02891 [hep-ph])
[7] de Salas P F, Forero D V, Ternes C A, Tortola M and Valle J W F 2018 Status of neutrino oscillations 2018: 3$\sigma$ hint for normal mass ordering and improved CP sensitivity Phys. Lett. B 782 633 (Preprint arXiv:1708.01186 [hep-ph])
[8] Esteban I, Gonzalez-Garcia M C, Maltoni M, Martinez-Soler I and Schwetz T 2017 Updated fit to three neutrino mixing: Exploring the accelerator-reactor complementarity J. High Energy Phys. 2017(87) doi:10.1007/JHEP01(2017)087 (Preprint arXiv:1611.01514 [hep-ph])
[9] Ayres D S, et al. 2007 The NOvA technical design report (United States: Fermi National Accelerator Lab.) doi:10.2172/935497
[10] Adamson P et al. 2017 Constraints on oscillation parameters from $\nu_e$ appearance and $\nu_\mu$ disappearance in NOvA Phys. Rev. Lett. 118 231801 (Preprint arXiv:1703.03328 [hep-ex])
[11] Acero M A et al. 2018 New constraints on oscillation parameters from $\nu_\mu$ appearance and $\nu_e$ disappearance in the NOvA experiment Phys. Rev. D 98 032012 (Preprint arXiv:1806.00096 [hep-ex])
[12] Aurisano A et al. 2016 A convolutional neural network neutrino event classifier Journal of Instrumentation 11(09) P09001
[13] Bassin C, Laske G, and Masters G 2000 The current limits of resolution for surface wave tomography in North America Eos Trans. AGU 81(48) F897
[14] Adamson P et al. 2017 Measurement of the neutrino mixing angle $\theta_{23}$ in NOvA Phys. Rev. Lett. 118 151802 (Preprint arXiv:1701.05891 [hep-ex])
[15] Abe K et al. 2017 Measurement of neutrino and antineutrino oscillations by the T2K experiment including a new additional sample of $\nu_\tau$ interactions at the far detector Phys. Rev. D 96 092006 2018 Erratum: Phys. Rev. D 98 019902 (Preprint arXiv:1707.01048 [hep-ex])
[16] Adamson P et al. 2014 Combined analysis of $\nu_\mu$ disappearance and $\nu_\mu \rightarrow \nu_e$ appearance in MINOS using accelerator and atmospheric neutrino oscillations Phys. Rev. Lett. 112 191801 (Preprint arXiv:1403.0867 [hep-ex])
[17] Aartsen M G et al. 2018 Measurement of atmospheric neutrino oscillations at 656 GeV with IceCube DeepCore Phys. Rev. Lett. 120 071801 (Preprint arXiv:1707.07081 [hep-ex])
[18] Abe K et al. 2018 Atmospheric neutrino oscillation analysis with external constraints in Super-Kamiokande I-IV Phys. Rev. D 97 072001 (Preprint arXiv:1710.09126 [hep-ex])
[19] Sanchez M 2018 NOvA results and prospects XXVIII International Conference on Neutrino Physics and Astrophysics (Heidelberg) (Switzerland: Zenodo) doi: 10.5281/zenodo.1286758 url: https://doi.org/10.5281/zenodo.1286758