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First neutrino oscillation measurements in NOvA

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Abstract

The NOvA experiment uses the Fermilab NuMI neutrino beam and a newly constructed 14 kt detector to address several open questions in neutrino oscillations including the neutrino mass hierarchy, the precise value of the angle θ_{23}, and the CP-violating phase δ_{CP}. The experiment has been running since 2014 and has recently released its first results from an equivalent exposure of 2.74×10^{20} protons-on-target equal to 8% of the eventual data set. Measurements of $\nu_\mu \to \nu_\mu$ oscillations find $\Delta m^2_{32} = (2.52^{+0.20}_{-0.18}) \times 10^{-3}$ eV^2 and $0.38 < \sin^2\theta_{23} < 0.65$ for the normal neutrino mass hierarchy. The experiment has observed $\nu_\mu \to \nu_e$ oscillations at 3.3 σ C.L. in this early data and disfavors the inverted neutrino mass hierarchy in the range $0.1\pi < \delta_{CP} < 0.5\pi$ at the 90% C.L.

1. Introduction

Following the discovery of neutrino oscillations [1,2], and hence neutrino mass, many experiments have used neutrinos from the atmosphere [3–5], the Sun [6–10], reactors [11–14], and accelerators [4,15–20] to test the oscillation model and elucidate the parameters of the oscillations. From this program, we now know that two neutrinos are relatively close in mass, separated by $\Delta m^2_{21} = +7.5 \times 10^{-5}$ eV^2 and a third is separated from these by a larger splitting $|\Delta m^2_{32}| = 2.4 \times 10^{-3}$ eV^2. We learned that the mixing angle most responsible for atmospheric

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neutrino oscillations is nearly maximal $\theta_{23} = 45°$ and that the angle most responsible for solar neutrino oscillations is also large, but not maximal $\theta_{12} = 33°$. Recently we have learned from reactor experiments and long-baseline experiments that the third angle, θ_{13}, though smaller than the others, is also a relatively large 8°. The focus of the current generation of experiments, which includes NOvA, is on the remaining unknowns: the sign of the mass splitting Δm^2_{32}, the precise value of θ_{23}, and the possibility that neutrino oscillations violate CP symmetry.

2. Neutrino oscillations in NOvA

The NOvA experiment uses the fact that the remaining questions in neutrino oscillations can be accessed through the study of $\nu_\mu \to \nu_e$ and $\bar{\nu}_\mu \to \bar{\nu}_e$ oscillations in matter at long baseline. Following [21], these probabilities can be written in a very good approximation as

$$P(\nu_\mu \to \nu_e) = P_{\text{atm}} + 2\sqrt{P_{\text{atm}} P_{\text{sol}}}(\cos\Delta_{32}\cos\delta_{\text{CP}} \mp \sin\Delta_{32}\sin\delta_{\text{CP}}) + P_{\text{sol}} \tag{1}$$

where here and elsewhere the top choice of sign is made for neutrinos and the bottom choice is made for antineutrinos. The direct oscillation probabilities associated with the atmospheric and solar mass-splittings are

$$\begin{aligned}\sqrt{P_{\text{atm}}} &= \sin\theta_{23}\sin 2\theta_{13}\frac{\sin(\Delta_{31} - aL)}{\Delta_{31} - aL}\Delta_{31},\\ \sqrt{P_{\text{sol}}} &= \cos\theta_{23}\sin 2\theta_{12}\frac{\sin(aL)}{aL}\Delta_{21}\end{aligned} \tag{2}$$

where the strength of the matter effect for electron number density N_{e} is parameterized by $a = \pm G_{\text{F}} N_{\text{e}}/\sqrt{2} \simeq 1/3500$ km in the Earth's crust. For NOvA $L = 810$ km, and $E \simeq 2$ GeV giving

$$\begin{aligned}\Delta_{32} \simeq \Delta_{31} &= \frac{1.27\Delta m^2_{32} L}{E} \simeq 1.1\\ \Delta_{21} &= \frac{1.27\Delta m^2_{21} L}{E} \simeq 0.04,\end{aligned} \tag{3}$$

for mass-squared splitting in units of eV^2.

Fig. 1 illustrates how measurements of both $P(\nu_\mu \to \nu_e)$ and $P(\bar{\nu}_\mu \to \bar{\nu}_e)$ by NOvA can resolve the θ_{23} octant, the neutrino mass hierarchy, and the value of δ_{CP}. P_{atm} sets the overall scale of the oscillation probabilities and depends on the combination $\sin^2\theta_{23}\sin^2 2\theta_{13}$. The value of $\sin^2(2\theta_{13})$ is now well known from reactor experiments [11–13], however, the value of $\sin^2\theta_{23}$ can vary between 0.4 and 0.6 as θ_{23} ranges through its current experimentally allowed values [22] in the lower octant, through maximal mixing ($\sin^2\theta_{23} = 0.5$), into the upper octant. The mass hierarchy is accessible through the term $\Delta_{31} - aL$ which beats the unknown sign of Δ_{31} against the known sign of aL. Interference between oscillations at the atmospheric scale and solar scale introduces a dependence on δ_{CP}.

3. The NOvA experiment

NOvA is the second long-baseline experiment to use the NuMI neutrino beam at Fermilab [23]. To enhance the size of the matter effect, and hence sensitivity to the mass hierarchy, the NOvA detector is located as far from the point of neutrino production as practically possible, $L =$ 810 km, at a site along the Ash River Trail in Minnesota. The NOvA beam line was deliberately