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Neutrino oscillations with MINOS and MINOS+

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Abstract

The MINOS experiment ran from 2003 until 2012 and collected a data sample including 10.71×10^{20} protons-on-target (POT) of beam neutrinos, 3.36×10^{20} POT of beam antineutrinos and an atmospheric neutrino exposure of 37.88 kt yrs. The final measurement of the atmospheric neutrino oscillation parameters, Δm^2_{32} and θ_{23}, came from a full three flavour oscillation analysis of the combined CC ν_μ and CC $\overline{\nu}_\mu$ beam and atmospheric samples and the CC ν_e and CC $\overline{\nu}_e$ appearance samples. This analysis yielded the most precise measurement of the atmospheric mass splitting Δm^2_{32} performed to date. The results are $|\Delta m^2_{32}| = [2.28\text{–}2.46] \times 10^{-3}\ \text{eV}^2$ (68%) and $\sin^2\theta_{23} = 0.35\text{–}0.65$ (90%) in the normal hierarchy, and $|\Delta m^2_{32}| = [2.32\text{–}2.53] \times 10^{-3}\ \text{eV}^2$ (68%) and $\sin^2\theta_{23} = 0.34\text{–}0.67$ (90%) in the inverted hierarchy. The successor to MINOS in the NOνA era at FNAL, MINOS+, is now collecting data mostly in the 3–10 GeV region, and an analysis of ν_μ disappearance using the first 2.99×10^{20} POT of data produced results very consistent with those from MINOS. Future data will further test the standard neutrino oscillation paradigm and allow for improved searches for exotic phenomena including sterile neutrinos, large extra dimensions and non-standard interactions.

1. Introduction

Nearly two decades have passed since the first observation of neutrino oscillations by Super-Kamiokande [1]. In that time it has become very clear from a number of experiments looking

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at neutrinos from the sun, the atmosphere, nuclear reactors and man-made neutrino beams that neutrinos can undergo oscillations from one flavour to another [2–14], as described by the PMNS matrix [15–17]. The PMNS matrix, U, commonly parametrised by three mixing angles (θ_{23}, θ_{12} and θ_{13}) and a CP-violating phase (δ_{CP}), describes the mixing between the three weak flavour eigenstates, $|\nu_\alpha\rangle$, and mass eigenstates, $|\nu_i\rangle$ in the following way:

$$|\nu_\alpha\rangle = \sum_{i=1}^{3} U_{\alpha i}|\nu_i\rangle. \tag{1}$$

The three mixing angles have been measured to varying degrees of accuracy but the value of δ_{CP} is still unknown. The oscillations arise from the quantum mechanical interference between the neutrino mass states and are driven by the mass-squared splittings between these mass states, $\Delta m^2_{ij} \equiv m^2_i - m^2_j$. It is possible to write down three mass-squared splittings, but only two are actually independent. One of the mass splittings, Δm^2_{21}, is considerably smaller than the others, meaning there are two scales at which oscillations can occur. The signs of the other mass-splittings, Δm^2_{32} and Δm^2_{31}, are currently unknown, meaning it is not known whether m_3 is the lightest or heaviest mass state. The case where it is the heaviest (lightest) is referred to as the normal (inverted) hierarchy. A final, important consequence of neutrino oscillations is the requirement that at least two of the neutrino mass states must be non-zero.

The two main oscillation channels of interest in long-baseline neutrino oscillation experiments are $\nu_\mu \to \nu_\mu$ disappearance and $\nu_\mu \to \nu_e$ appearance. These channels were first probed using a man-made neutrino beam by the K2K experiment [5,18]. The discovery of $\nu_\mu \to \nu_e$ oscillations was performed by T2K [8] and $\nu_\mu \to \nu_\tau$ appearance was discovered by the OPERA experiment [19]. Oscillations in such experiments are driven by the two larger mass-splittings, Δm^2_{32} and Δm^2_{31}. Using a two neutrino approximation, with the parameters Δm^2 and $\sin^2 2\theta$, the ν_μ disappearance probability for a neutrino with energy E and travelling over a distance L in the vacuum can be written as follows:

$$P(\nu_\mu \to \nu_\mu) = 1 - \sin^2 2\theta \sin^2\left(\frac{\Delta m^2 L}{4E}\right). \tag{2}$$

However, θ_{13} was measured by Daya Bay [12] and later by RENO [13] and Double CHOOZ [14] and is hence known to be reasonably large. In addition, the uncertainty on measurements of Δm^2_{32} is of the same order as the size of Δm^2_{21}. The more accurate formalism requires the use of the full three flavour oscillation probabilities and the approximate parameters Δm^2 and $\sin^2 2\theta$ in Eq. (2) are modified in the following way [20]:

$$\begin{aligned}\sin^2 2\theta &= 4\cos^2\theta_{13}\sin^2\theta_{23}(1-\cos^2\theta_{13}\sin^2\theta_{23}),\\ \Delta m^2 &= \Delta m^2_{32} + \sin^2\theta_{12}\Delta m^2_{21} + \cos\delta_{CP}\sin\theta_{13}\sin 2\theta_{12}\tan\theta_{23}\Delta m^2_{21}.\end{aligned} \tag{3}$$

The expressions given in Eq. (3) illustrate how the interference between the two different mass-splitting terms causes the full oscillation probability to depend on all of the parameters of the PMNS matrix. It can be seen in Eq. (2) that the two flavour oscillation probability is symmetric under the transformations of $\theta \to \frac{\pi}{2} - \theta$ and $\Delta m^2 \to -\Delta m^2$. The equivalent parameter shifts for the three flavour case in Eq. (3) are $\theta_{23} \to \frac{\pi}{2} - \theta_{23}$ and $\Delta m^2_{32} \to -\Delta m^2_{32}$, and it can be seen that the oscillation probability is not completely symmetric under these transformations, leading to approximate degeneracies instead of symmetries.

When neutrinos traverse matter, the Hamiltonian associated with the propagation is modified compared to that of the vacuum by interactions of the neutrinos with the matter. All three neutrino