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The discovery of the appearance of $\nu_\mu - \nu_\tau$ oscillations

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Abstract

Almost 20 years after the first conceptual design of the experiment, five years of running in the Gran Sasso underground laboratory (LNGS), and billions of billions muon-neutrinos sent from CERN along the CNGS beam, in 2015 the OPERA neutrino detector has allowed the long-awaited discovery of the direct transformation (oscillation) of muon-neutrinos into tau-neutrinos. This result unambiguously confirms the interpretation of the so-called atmospheric channel, after the discovery of neutrino oscillations by the Super-Kamiokande Collaboration in 1998.

1. Introduction

Neutrino oscillations were originally proposed by Bruno Pontecorvo for the neutrino–antineutrino oscillation mode around the end of the fifties of the last century, when only one neutrino flavor was known [1]. A few years later, soon after the discovery of the ν_μ [2] a mixing-scheme between ν_e and ν_μ with two states called "true" neutrinos ν_1 and ν_2, was proposed by Ziro Maki, Masami Nakagawa and Shoichi Sakata [3], within the so-called Nagoya Model [4]. Mixing among massive neutrinos occurs as for quarks, as first proposed by Nicola Cabibbo and then extended by Makoto Kobayashi and Toshihide Maskawa. This hypothesis, well supported by the experimental data, led to the Cabibbo–Kobayashi–Maskawa (CKM) quark mixing-matrix [5]. For neutrino mixing we talk today of the Pontecorvo–Maki–Nakagawa–Sakata (PMNS) matrix. After the discovery of the second neutrino flavor, partner of the muon, the concept of a third

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family came about with the new charged τ lepton and its corresponding tau-neutrino. It took 25 years to discover the third neutrino with the DONUT experiment conducted by Kimio Niwa and collaborators at Fermilab [6].

The flavor conversion (oscillation) between neutrino weak eigenstates (ν_e, ν_μ and ν_τ) can occur provided the neutrino is a massive particle and non-vanishing, non-degenerate mass eigenstates (ν_1, ν_2 and ν_3) exist. The two sets of eigenstates mix through the PMNS mixing matrix and one can then obtain a periodic flavor variation during neutrino propagation in space and time. The PMNS matrix includes angles, which appear in the oscillation probability relations experimentally tested between different flavor eigenstates. The original oscillation formalism deals with neutrinos oscillating in vacuum. For matter propagation a different formula should be adopted, as the MSW relations [7], which is applied, in particular, to electron-neutrino propagation in the dense solar matter.

If we restrict ourselves to vacuum oscillations, a reasonable approximation for most terrestrial experiments, we are left with 3 independent mixing angles: θ_{12} experimentally associated to the solar neutrino oscillations, θ_{23} connected to the atmospheric neutrino oscillations, and the θ_{13} angle that constitutes the "link" between the two leading oscillation channels. The fact that the latter angle is larger than zero allows detecting a possible non-vanishing CP violating phase δ in the matrix. Two independent values of the squared mass eigenvalue differences $(m_i^2 - m_j^2)$, Δm_{12}^2 and Δm_{23}^2, respectively associated to the solar and atmospheric sectors, complete the oscillation parameters to be measured by the experiments. We have to finally add the baseline L and the energy of the neutrinos E, both in principle fixed by the experimental conditions. The oscillation formula amplitude is then a function of the mixing angles, while the frequency of the oscillation depends on the Δm^2 parameters and L/E.

After the discovery of the oscillations by the Super-Kamiokande Collaboration with atmospheric neutrinos [8] and relevant experimental results from many more experiments, global fits have been produced including all neutrino oscillation results obtained with natural and artificial neutrinos [9]. The consequent flavor composition of the mass neutrino eigenstates can then be derived for both the possible cases of normal and inverted mass hierarchy: $m(\nu_3) > m(\nu_2) > m(\nu_1)$ and $m(\nu_2) > m(\nu_1) > m(\nu_3)$.

The one just briefly described is the "Standard Neutrino Oscillation Model". However, some experimental hints accumulated in the last two decades seem to point to the possible existence of another Δm^2 associated to an additional oscillation amplitude, coming from short baseline and reactor oscillation experiments. Obviously, this cannot be accommodated by assuming a simple 3×3 matrix that mixes the three known neutrino flavors. For this reason, one should advocate the existence of at least a fourth neutrino in Nature. Given the fact that no charged current reactions induced by such a neutrino have ever been observed, one postulates that it is a sterile particle, only coupling to the other fermions (standard neutrinos) through the oscillation mechanism. Several experiments are searching for sterile neutrinos with different experimental techniques. As an example, I mention the SBN program at Fermilab [10].

The most general oscillation formula can be approximated for two notable oscillation channels, namely $\nu_\mu - \nu_\tau$ appearance studied by the OPERA experiment, and $\nu_\mu - \nu_e$, explored by the T2K [11] and NOvA [12] experiments:

$$P(\nu_\mu - \nu_\tau) \sim \cos^4\theta_{13} \sin^2 2\theta_{23} \sin^2\left(\Delta m_{23}^2 L/4E\right)$$

$$P(\nu_\mu - \nu_e) \sim \sin^2 2\theta_{13} \sin^2\theta_{23} \sin^2\left(\Delta m_{23}^2 L/4E\right)$$