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Neutrino oscillations: From a historical perspective to the present status

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Abstract

The history of neutrino mixing and oscillations is briefly presented. Basics of neutrino mixing and oscillations and convenient formalism of neutrino oscillations in vacuum are given. The role of neutrino in the Standard Model and the Weinberg mechanism of the generation of the Majorana neutrino masses are discussed.

1. Introduction. On the history of neutrino oscillations

Discovery of the neutrino oscillations in the atmospheric Super-Kamiokande [1], solar SNO [2] and reactor KamLAND [3] experiments was a first evidence in favor of a beyond the Standard Model physics in particle physics. Neutrino oscillations were further studied in the long baseline accelerator K2K [4], MINOS [5] and T2K [6] experiments. With the measurement of the small parameter $\sin^2\theta_{13}$ in the accelerator T2K [6], reactor Daya Bay [7], RENO [8] and Double Chooze [9] experiments investigation of neutrino oscillations enters a new era, era of high precision measurements. The 2015 Nobel Prize to T. Kajita and A. McDonald "for the discovery

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of neutrino oscillations, which shows that neutrinos have mass" is a very important event for the neutrino community which will attract new people and give a great boost to the field.

Idea of neutrino oscillations was first proposed by B. Pontecorvo in 1957–1958 soon after the theory of the two-component neutrino was proposed [10] and confirmed by the Goldhaber et al. experiment [11]. B. Pontecorvo looked in the lepton world for a phenomenon analogous to $K^0 \leftrightarrows \bar{K}^0$ oscillations. In the paper [12] he considered muonium ($\mu^+ e^-$) to antimuonium ($\mu^- e^+$) transition. In this paper he mentioned a possibility of the neutrino oscillations. Special paper dedicated to neutrino oscillations was published by B. Pontecorvo in 1958 [13]. At that time only one type of neutrino was known. B. Pontecorvo assumed that in addition to the usual weak interaction *there must exist a much weaker interaction which does not conserve the lepton number.* Assuming maximum mixing (by the analogy with $K^0 - \bar{K}^0$) he concluded that "...neutrino and antineutrino are particle mixtures, i.e. symmetrical and antisymmetrical combinations of two truly neutral Majorana particles ν_1 and ν_2...":

$$|\bar{\nu}_R\rangle = \frac{1}{\sqrt{2}}(|\nu_1\rangle + |\nu_2\rangle), \quad |\nu_R\rangle = \frac{1}{\sqrt{2}}(|\nu_1\rangle - |\nu_2\rangle). \tag{1}$$

Here $|\bar{\nu}_R\rangle$ is the state of the right-handed antineutrino, $|\nu_R\rangle$ is the state of right-handed neutrino, a particle which does not take part in the weak interaction (later B. Pontecorvo proposed the name sterile for such neutrinos), $|\nu_{1,2}\rangle$ are states of Majorana neutrinos with small masses $m_{1,2}$. As a result of the mixing (1), oscillations $\bar{\nu}_R \leftrightarrows \nu_R$ (sterile) become possible. B. Pontecorvo discussed a possibility to check a hypothesis of neutrino oscillations in the reactor neutrino experiments. In 1958 the only known sources of neutrinos were reactors and the sun. B. Pontecorvo finished the paper [13] with the following remark "...effects of transformation of neutrino into antineutrino and vice versa may be unobservable in the laboratory because of large values of R (oscillation length), but will certainly occur, at least, on an astronomic scale."

In 1962 the idea of neutrino masses and mixing was discussed by Maki, Nakagawa and Sakata [14]. Their proposal was based on the Nagoya model in which nucleons were considered as bound states of a vector boson and neutrino with definite mass. MNS assumed that the fields of the weak neutrinos ν_e and ν_μ are connected with the fields of neutrinos with definite masses ν_1 and ν_2 (they called them true neutrinos) by the orthogonal transformation

$$\nu_e = \cos\theta\,\nu_1 + \sin\theta\,\nu_2, \quad \nu_\mu = -\sin\theta\,\nu_1 + \cos\theta\,\nu_2. \tag{2}$$

The phenomenon of neutrino oscillations was not considered in [14]. However, MNS discussed a possibility of "virtual transmutation" of ν_μ into ν_e. They estimated a time of this transition and discussed how a possible $\nu_\mu \to \nu_e$ transition would influence the interpretation of the results of the Brookhaven experiment [15],[1] which was going on at the time when the MNS paper was written.

In 1967 B. Pontecorvo published the second paper on neutrino oscillations [16]. In this paper he discussed flavor neutrino oscillations $\nu_\mu \leftrightarrows \nu_e$ and also oscillations between flavor and sterile neutrinos ($\nu_{eL} \leftrightarrows \bar{\nu}_{eL}$, etc.). In the paper [16] solar neutrino oscillations were considered. *Before the first results of the Davis solar neutrino experiment appeared*, B. Pontecorvo pointed out that because of neutrino oscillations the flux of the solar ν_e's could be two times smaller than the expected flux. Thus, he anticipated "the solar neutrino problem".

In the Gribov and Pontecorvo paper [17] it was suggested that only active left-handed neutrinos ν_e and ν_μ and right-handed antineutrinos $\bar{\nu}_e$ and $\bar{\nu}_\mu$ exist in nature (no sterile neutrinos). It

[1] As it is well known, in this experiment it was discovered that ν_μ and ν_e are different particles.