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# Neutrino oscillations: An experimental review

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**Summary.** — In this paper we summarize the status of neutrino-oscillation searches from an experimentalist point of view emphasizing the latest results. In particular we report about the Borexino, MINOS, OPERA and MiniBoone results. A brief outlook on the perspectives of this field of research is also given.

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## 1. – Introduction

The experimental evidences for neutrino oscillations collected in the last fifteen years represent a major discovery in modern particle physics. The oscillation phenomenon allows the measurement of fundamental parameters of the Standard Model and provides the first insight beyond the electroweak scale [1]. Moreover, they are important for many fields of astrophysics and cosmology and open the possibility to study $CP$ violation in the leptonic sector [2].

Neutrino flavor oscillations can be described in terms of three mass eigenstates $\nu_1$, $\nu_2$, $\nu_3$ with mass values $m_1$, $m_2$ and $m_3$ that are connected to the flavor eigenstates $\nu_e$, $\nu_\mu$ and $\nu_\tau$ by a mixing matrix $U$ (from now on indicated as the PMNS (Pontecorvo, Maki, Nakagawa and Sakata) matrix), usually parameterized as

$$U(\theta_{12},\theta_{23},\theta_{13},\delta_{CP}) = \begin{pmatrix} c_{13}c_{12} & c_{13}s_{12} & s_{13}e^{-i\delta_{CP})} \\ -c_{23}s_{12}-s_{13}s_{23}c_{12}e^{i\delta_{CP})} & c_{23}c_{12}-s_{13}s_{23}s_{12}e^{i\delta_{CP})} & c_{13}s_{23} \\ s_{23}s_{12}-s_{13}c_{23}c_{12}e^{i\delta_{CP})} & -s_{23}c_{12}-s_{13}c_{23}s_{12}e^{i\delta_{CP})} & c_{13}c_{13} \end{pmatrix} \quad (1)$$

where the short-form notation $s_{ij} \equiv \sin\theta_{ij}$, $c_{ij} \equiv \cos\theta_{ij}$ is used. As a result, the neutrino-oscillation probability depends on 3 mixing angles, $\theta_{12}$, $\theta_{23}$, $\theta_{13}$, 2 mass differences, $\Delta m^2_{12} = m^2_2 - m^2_1$, $\Delta m^2_{23} = m^2_3 - m^2_2$, and a $CP$ phase $\delta_{CP}$. Additional phases are present in case neutrinos are Majorana particles, but they do not influence at all neutrino flavor oscillations. Furthermore, the neutrino mass hierarchy, the ordering with which mass eigenstates are coupled to flavor eigenstates, can be fixed by measuring the sign of $\Delta m^2_{23}$. In vacuum the oscillation probability between two neutrino flavors $\alpha$, $\beta$ is

$$(2) \qquad P(\nu_\alpha \to \nu_\beta) = -4\sum_{k>j} \mathrm{Re}\left[W^{jk}_{\alpha\beta}\right]\sin^2\frac{\Delta m^2_{jk}L}{4E_\nu} \pm 2\sum_{k>j} \mathrm{Im}\left[W^{jk}_{\alpha\beta}\right]\sin^2\frac{\Delta m^2_{jk}L}{2E_\nu},$$

where $\alpha = e, \mu, \tau$, $j = 1, 2, 3$, $W^{jk}_{\alpha\beta} = U_{\alpha j}U^*_{\beta j}U^*_{\alpha k}U_{\beta k}$. In the case of only two-neutrino flavor oscillation it can be written as

$$(3) \qquad P(\nu_\alpha \to \nu_\beta) = \sin^2 2\theta \cdot \sin^2\frac{1.27\ \Delta m^2(\mathrm{eV}^2)\cdot L(\mathrm{km})}{E_\nu(\mathrm{GeV})}.$$

Therefore two experimental parameters are relevant for neutrino oscillations: the neutrino energy $E_\nu$ and the baseline $L$ (distance of the neutrino source from the detector); in the oscillation formula they are combined into the $L/E_\nu$ ratio. When neutrinos pass through matter, the oscillation probability is perturbed (the so-called MSW effect [3]) depending on sign($\Delta m^2_{23}$) [4].

## 2. – Recent results

The years from 1998 to 2006 are oftern referred as the "Golden Age" of neutrino physics. Indeed, about fifty years after the neutrino oscillation phenomenon was postulated by B. Pontecorvo [5], the Super-Kamiokande [6] finally unambiguously discovered the neutrino oscillations. Since then, may experiments seeking for neutrino oscillations have been carried out contributing to the understanding of the PMNS matrix, see [7] for a review.

**2**˙1. *Solar neutrinos.* – The Super-Kamiokande [8], SNO [9] and Kamland [10] results settled the long-standing solar-neutrino problem showing that our understanding of the solar physics is correct and that electron neutrinos change their flavour in traveling from the Sun to the Earth. In particular, the range of parameters describing the oscillation phenomenon has been constrained to the so-called LMA (large angle mixing) region of the plane $(\theta_{12}, \Delta m_{12})$. Matter effects in the Sun play an important role. In particular, the LMA solution tells us that neutrino oscillations are dominated by vacuum oscillations at low energies ($< 1$ MeV) and by resonant matter-enhanced oscillations, taking place in the core of the Sun, at higher energies ( 5 MeV). Given its extreme radiopurity, the Borexino experiment is able to detect real-time neutrinos down to an energy threshold of 2.8 MeV [11]. Therefore, it has been able to investigate simultaneously solar neutrinos both in the vacuum-dominated ($^7$Be $\nu$) and matter-enhanced regions ($^8$B $\nu$). The obtained results for $P_{ee}$ (the survival probability) are shown in fig. 1 and compared with expectations due to MSW-LMA theory. The agreement is good and confirms the vacuum to matter-enhanced oscillation transition of solar neutrinos [12].

**2**˙2. *Accelerator and reactor neutrinos.* – Several detectors are presently running on artificial neutrino beams. Actually, some of them (MINOS, OPERA, MiniBoone) recently published new results that will be summarized here below. The status of T2K [13], ICARUS [14] and reactor experiments will not be covered and we refer to the quoted references for details.

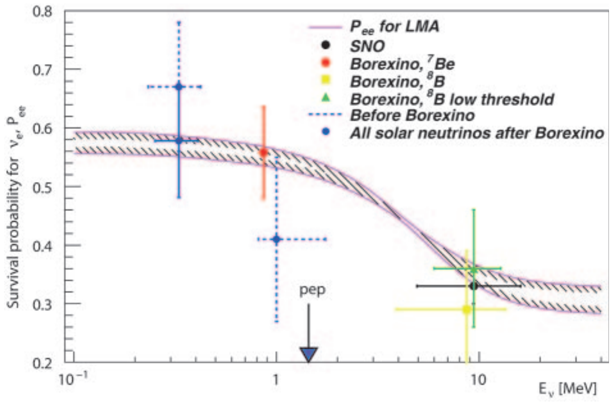


Fig. 1. – $^7$Be and $^8$B electron survival probability as measured by Borexino compared to the previous measurements and MSW-LMS predictions.

MINOS [15] is a two-detector experiment to study neutrino oscillations in the NuMI high-intensity neutrino beam at the Fermi National Accelerator Laboratory. The $\nu_\mu$ disappearance analysis has been firstly released in 2008 and recently upgraded by doubling the statistics. The MINOS data yielded a measurement of the mixing parameters $(\theta_{23}, \Delta m_{23})$ with an accuracy never reached before and consistent with the atmospheric neutrino experiments. The same data strongly disfavor with a significance larger than $7\sigma$ both pure neutrino decay and pure decoherence.

Very recently the a $\bar{\nu}_\mu$ disappearance search has been also performed by using the NuMI beam in the so-called anti-neutrino configuration, where the $\bar{\nu}_\mu$ content of the beam is about 40%, much larger than in the neutrino configuration, 7%. Although the antineutrino beam is not optimized for oscillation searches, the $\bar{\nu}_\mu$ energy spectrum has been reconstructed and the mixing parameters extracted. This is the first direct observation of $\bar{\nu}_\mu$ disappearance of an accelerator experiment and shows a difference in the $\nu_\mu$ and $\bar{\nu}_\mu$ survival probabilities with a significance of $1.9\sigma$. Note that if $CPT$ is conserved then the survival probability is identical for neutrinos and antineutrinos. An antineutrino run is still in progress with the aim of increasing the statistics.

MINOS also performed a search for $\nu_e$ appearance. The challenge is to find a small signal in the presence of a large background. After an initial excess of $\nu_e$ observed with a limited statistics, the analysis of the complete neutrino sample only showed an excess of $0.7\sigma$ over the expected background. When fitted to the $\nu_\mu \to \nu_e$ oscillation hypothesis, this excess translates into an upper limit at 90% CL on $\sin^2 2\theta_{13}$ of 0.12(0.20) for normal (inverted) hierarchy.

The OPERA experiment [16] aims at measuring the first detection of neutrino oscillation in appearance mode through the detection of $\nu_\tau$ in an almost pure $\nu_\mu$ beam produced at CERN SPS (CNGS), 730 km far from the detector. The $\nu_\tau$ appearance signal is detected through the measurement of the decay daughter particles of the $\tau$ lepton produced in CC $\nu_\tau$ interactions. Since the short-lived $\tau$ particle has, at the energy of the beam, an average decay length of about 1 mm, a micrometric detection resolution is needed. Runs with CNGS neutrinos were successfully carried out in 2007, 2008 and 2009 with the detector fully operational with its related facilities for the emulsion handling and analysis. In 2010 the run is in progress and will last until the end of November.

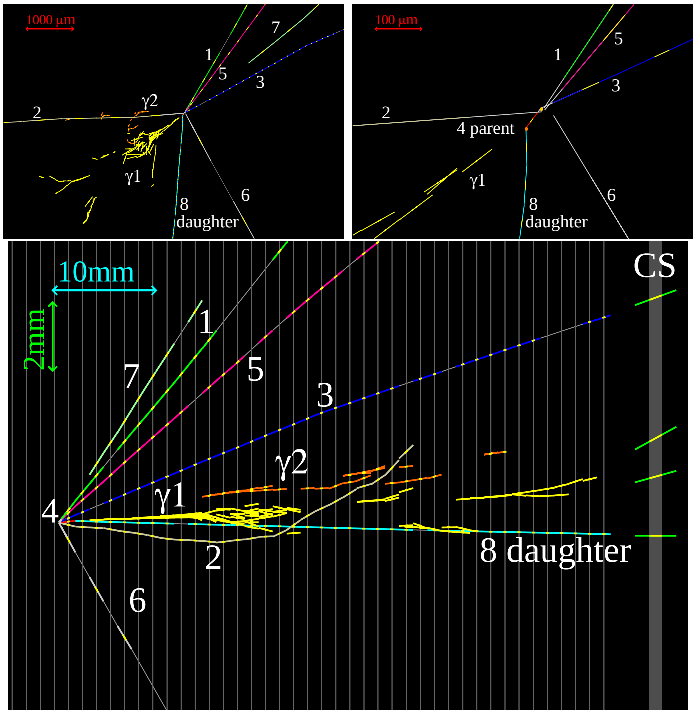


Fig. 2. – Display of the $\tau^-$ candidate event. Top left: view transverse to the neutrino direction. Top right: same view zoomed on the vertices. Bottom: longitudinal view.

Recently, the OPERA Collaboration reported the observation of a first candidate $\nu_\tau$ CC interaction in the OPERA detector at LNGS [17]. The primary neutrino interaction consists of 7 tracks of which one exhibits a visible kink. Two electromagnetic showers caused by $\gamma$-rays have been located that are associated with the event and in particular produced at the decay vertex. Figure 2 shows a display of the event. It was identified in a sample of events corresponding to $1.89 \times 10^{19}$ p.o.t. in the CERN CNGS $\nu_\mu$ beam. The total transverse momentum $P_T$ of the daughter particles with respect to the parent track is $(0.47^{+0.24}_{-0.12})\,\mathrm{GeV}/c$, above the lower selection cut-off at $0.3\,\mathrm{GeV}/c$. The missing transverse momentum $P_T^{miss}$ at the primary vertex is $(0.57^{+0.32}_{-0.17})\,\mathrm{GeV}/c$. This is lower than the upper selection cut-off at $1\,\mathrm{GeV}/c$. The angle $\Phi$ between the parent track and the rest of the hadronic shower in the transverse plane is equal to $(3.01 \pm 0.03)$ rad, largely above the lower selection cut-off fixed at $\pi/2$. The invariant mass of $\gamma$-rays 1 and 2 is $(120 \pm 20(stat.) \pm 35(syst.))\,\mathrm{MeV}/c^2$, supporting the hypothesis that they originate from a $\pi^0$ decay. Similarly the invariant mass of the charged decay product assumed to be a $\pi^-$ and of the two $\gamma$-rays is $(640^{+125}_{-80}(stat.)^{+100}_{-90}(syst.))\,\mathrm{MeV}/c^2$, which is compatible with the $\rho(770)$ mass. The branching ratio of the decay mode $\tau \to \rho^- \nu_\tau$ is about 25%. Therefore, the assumed $\tau^-$ lepton decays into $h^-(n\pi^0)\nu_\tau$. The observation of one possible tau candidate in the decay channel $h^-(\pi^0)\nu_\tau$ has a significance of $2.36\sigma$ of not being a background fluctuation (background in this channel $0.018 \pm 0.007$). If one considers all decay modes included in the search the significance of the observation becomes $2.01\sigma$, being the total background $0.045 \pm 0.023$.

In 1995 the LSND Collaboration claimed the observation of $\bar{\nu}_\mu \to \bar{\nu}_e$ channel at a scale of $\Delta m^2 \simeq 0.1\,\mathrm{eV}^2$ [18] with a statistical significance of $3.8\sigma$. However, this evidence was not confirmed by the KARMEN Collaboration [19]. In order to test the LSND result, a new experiment, MiniBoone, has been built and ran at FNAL. After a first result not confirming the LSND evidence [20], recently the MiniBoone Collaboration presented an analysis based on a statistics twice larger than before and an excess of $\bar{\nu}_e$ has been observed [21]. It is still 3% compatible with the null result, therefore a new run is in progress in order to double the statistics. If the excess is confirmed, either the 3-family schema has to be abandoned or new phenomena have to be advocated to explain it.

## 3. – Outlook and conclusion

The present knowledge of the PMNS is well summarized in ref. [22]. The numerical values of the matrix elements are given herein the following:

| GS98 with gallium cross-section | AGSS09 with modified gallium cross-section |
|---|---|
| $\Delta m^2_{21} = 7.59 \pm 0.20 \left(^{+0.61}_{-0.69}\right) \times 10^{-5}\ \mathrm{eV}^2$ | Same |
| $\Delta m^2_{31} = \begin{cases} -2.36 \pm 0.11\,(\pm 0.37) \times 10^{-3}\ \mathrm{eV}^2 \\ +2.46 \pm 0.12\,(\pm 0.37) \times 10^{-3}\ \mathrm{eV}^2 \end{cases}$ | Same |
| $\theta_{12} = 34.4 \pm 1.0 \left(^{+3.2}_{-2.9}\right)^\circ$ | $34.5 \pm 1.0 \left(^{+3.2}_{-2.8}\right)^\circ$ |
| $\theta_{23} = 42.8^{+4.7}_{-2.9} \left(^{+10.7}_{-7.3}\right)^\circ$ | Same |
| $\theta_{13} = 5.6^{+3.0}_{-2.7}\,(\leq 12.5)^\circ$ | $5.1^{+3.0}_{-3.3}\,(\leq 12.0)^\circ$ |
| $\left[\sin^2\theta_{13} = 0.0095^{+0.013}_{-0.007}\,(\leq 0.047)\right]$ | $\left[0.008^{+0.012}_{-0.007}\,(\leq 0.043)\right]$ |
| $\delta_{CP} \in [0,\ 360]$ | Same |

Although gigantic step forward have been achieved in the past fifteen years and the recent observation of a $\tau$ candidate from the appearance of a $\nu_\tau$ in a pure $\nu_\mu$ in the OPERA experiment, there are still two unknown angles ($\theta_{13}$ and $\delta_{CP}$), the mass hierarchy is still to be determined, the evidence for neutrino oscillations in the $\bar{\nu}_\mu \to \bar{\nu}_e$ channel at a scale of $\Delta m^2 \simeq 0.1\,\mathrm{eV}^2$ is still debated and needs more solid confirmation. Furthermore, the absolute neutrino mass is still unknown.

In the coming year the T2K experiments should provide an unambiguous evidence for a non-zero $\theta_{13}$ if above 3°. The discovery of a non-zero value for $\theta_{13}$ will disclose the possibility to search for $CP$ violation in the leptonic sector. Many ideas have been put forward to measure a non-zero value of $\delta_{CP}$: Super-Beams, Beta-Beams and Neutrino Factory.

For a comprehensive review, with emphasis on the possible european contribution, we refer to [23] and references therein.

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