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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.

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 ν_1 , ν_2 , ν_3 with mass values m_1 , m_2 and m_3 that are connected to the flavor eigenstates ν_e , ν_{μ} and ν_{τ} by a mixing matrix U (from now on indicated as the PMNS (Pontecorvo, Maki, Nakagawa and Sakata) matrix), usually parameterized as

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

where the short-form notation $s_{ij} \equiv \sin \theta_{ij}$, $c_{ij} \equiv \cos \theta_{ij}$ is used. As a result, the neutrinooscillation probability depends on 3 mixing angles, θ_{12} , θ_{23} , θ_{13} , 2 mass differences, $\Delta m_{12}^2 = m_2^2 - m_1^2$, $\Delta m_{23}^2 = m_3^2 - m_2^2$, and a *CP* phase δ_{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

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mass eigenstates are coupled to flavor eigenstates, can be fixed by measuring the sign of Δm_{23}^2 . In vacuum the oscillation probability between two neutrino flavors α , β is

(2)
$$P(\nu_{\alpha} \to \nu_{\beta}) = -4\sum_{k>j} \operatorname{Re}\left[W_{\alpha\beta}^{jk}\right] \sin^{2}\frac{\Delta m_{jk}^{2}L}{4E_{\nu}} \pm 2\sum_{k>j} \operatorname{Im}\left[W_{\alpha\beta}^{jk}\right] \sin^{2}\frac{\Delta m_{jk}^{2}L}{2E_{\nu}}$$

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

Therefore two experimental parameters are relevant for neutrino oscillations: the neutrino energy E_{ν} and the baseline L (distance of the neutrino source from the detector); in the oscillation formula they are combined into the L/E_{ν} ratio. When neutrinos pass through matter, the oscillation probability is perturbed (the so-called MSW effect [3]) depending on sign(Δm_{23}^2) [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 (⁷Be ν) and matter-enhanced regions (⁸B ν). 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.

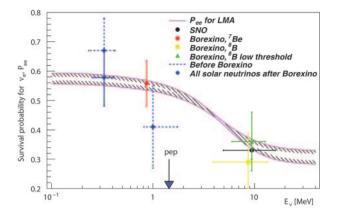


Fig. 1. - ⁷Be and ⁸B electron survival probability as measured by Borexino compared to the previous measurements and MSW-LMS predictions.

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 ν_{μ} 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 7σ 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 ν_{μ} and $\bar{\nu}_{\mu}$ survival probabilities with a significance of 1.9σ . 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 ν_e appearance. The challenge is to find a small signal in the presence of a large background. After an initial excess of ν_e observed with a limited statistics, the analysis of the complete neutrino sample only showed an excess of 0.7σ over the expected background. When fitted to the $\nu_{\mu} \rightarrow \nu_e$ 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 ν_{τ} in an almost pure ν_{μ} beam produced at CERN SPS (CNGS), 730 km far from the detector. The ν_{τ} appearance signal is detected through the measurement of the decay daughter particles of the τ lepton produced in CC ν_{τ} interactions. Since the short-lived τ 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.

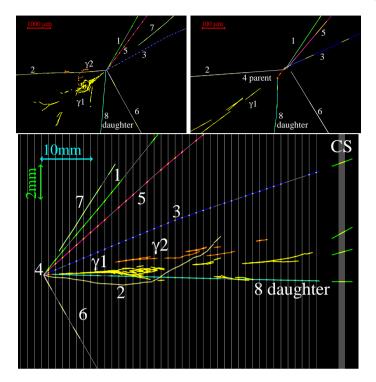


Fig. 2. – Display of the τ^- candidate event. Top left: view transverse to the neutrino direction. Top right: same view zoomed on the vertices. Bottom: longitudinal view.

Recently, the OPERA Collaboration reported the observation of a first candidate ν_{τ} 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 γ -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 1.89×10^{19} p.o.t. in the CERN CNGS ν_{μ} beam. The total transverse momentum P_T of the daughter particles with respect to the parent track is $(0.47^{+0.24}_{-0.12}) \text{ GeV}/c$, above the lower selection cut-off at 0.3 GeV/c. The missing transverse momentum P_T^{miss} at the primary vertex is $(0.57^{+0.32}_{-0.17}) \text{ GeV}/c$. This is lower than the upper selection cut-off at $1 \,\text{GeV}/c$. The angle Φ between the parent track and the rest of the hadronic shower in the transverse plane is equal to (3.01 ± 0.03) rad, largely above the lower selection cut-off fixed at $\pi/2$. The invariant mass of γ -rays 1 and 2 is $(120 \pm 20(stat.) \pm 35(syst.))$ MeV/ c^2 , supporting the hypothesis that they originate from a π^0 decay. Similarly the invariant mass of the charged decay product assumed to be a π^- and of the two γ -rays is $(640^{+125}_{-80}(stat.)^{+100}_{-90}(syst.)) \text{ MeV}/c^2$, 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 τ^- 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 σ of not being a background fluctuation (background in this channel 0.018 ± 0.007). If one considers all decay modes included in the search the significance of the observation becomes 2.01σ , being the total background 0.045 ± 0.023 .

In 1995 the LSND Collaboration claimed the observation of $\bar{\nu}_{\mu} \rightarrow \bar{\nu}_{e}$ channel at a scale of $\Delta m^{2} \simeq 0.1 \,\mathrm{eV}^{2}$ [18] with a statistical significance of 3.8σ . 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

GS98 with gallium cross-section	AGSS09 with modified gallium cross-section
$\Delta m_{21}^2 = 7.59 \pm 0.20 \ \binom{+0.61}{-0.69} \times 10^{-5} \ \mathrm{eV}^2$	Same
$\Delta m_{31}^2 = \begin{cases} -2.36 \pm 0.11 (\pm 0.37) \times 10^{-3} \mathrm{eV}^2 \\ +2.46 \pm 0.12 (\pm 0.37) \times 10^{-3} \mathrm{eV}^2 \end{cases}$	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
$\theta_{13} = 5.6^{+3.0}_{-2.7} (\le 12.5)^{\circ}$	$5.1^{+3.0}_{-3.3} (\le 12.0)^{\circ}$
$\left[\sin^2\theta_{13} = 0.0095^{+0.013}_{-0.007} (\le 0.047)\right]$	$\left[0.008^{+0.012}_{-0.007} (\le 0.043)\right]$
$\delta_{CP} \in [0, 360]$	Same

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

Although gigantic step forward have been achieved in the past fifteen years and the recent observation of a τ candidate from the appearance of a ν_{τ} in a pure ν_{μ} in the OPERA experiment, there are still two unknown angles (θ_{13} and δ_{CP}), the mass hierarchy is still to be determined, the evidence for neutrino oscillations in the $\bar{\nu}_{\mu} \rightarrow \bar{\nu}_{e}$ 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 θ_{13} if above 3°. The discovery of a non-zero value for θ_{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 δ_{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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