Available online at www.sciencedirect.com

ScienceDirect

Nuclear and Particle Physics Proceedings 273–275 (2016) 92–99

www.elsevier.com/locate/nppp

# Neutrino experiments : highlights of accelerator and reactor results

Marco Zito

*CEA-Saclay, IRFU/DSM, 91191 Gif-sur-Yvette CEDEX France*

**Abstract**

We present a summary of recent accelerator and reactor results in the field of neutrino experiments. Having established neutrino oscillations in a variety of experimental configurations, it is remarkable that practically all the observations fit within a well defined paradigm, where the neutrino mixing matrix PMNS plays a central role. The experimental task is today to precisely measure the parameters of this matrix and to make precision tests of this paradigm. Various experimental results, in particular the $\theta_{13}$ measurement at reactor experiments, are shown which illustrate that the few percent precision level has been reached or will be soon reached. This opens up a new realm of sensitivity to subleading effects in the oscillation phenomena. Moreover, the study of $\nu_\mu \to \nu_e$ appearance at accelerator experiments provides very preliminary indications related to the CP violation parameter $\delta_{CP}$. The full exploration of CP violation in the lepton sector is the goal for the future studies, with a contribution from various experiments, currently running or planned for the next decade.

*Keywords:* neutrino oscillations, neutrino mixing matrix, CP violation

## 1. Introduction

Neutrino physics has already provided us important discoveries and surprising results in the last decade. First, thanks to the discovery of neutrino oscillations it is now an established fact that neutrinos are massive. However, their mass is extremely low, certainly below the eV scale. This sets neutrinos aside from the other Standard Model fermions and requires an explanation. Indeed, the mere existence of a neutrino mass term points to physics beyond the Standard Model that needs to be understood. Second, there is now relatively good knowledge of the neutrino mixing matrix. The angles governing this matrix are large, the smallest being the $\theta_{13}$ angle, approximately 9 degrees. The situation is therefore considerably different than for the CKM mixing matrix relevant for the quark sector. We can further notice that neutrinos, the most abundant fermions in the Universe according to our current theoretical framework, play a fundamental role in the evolution of the Universe and in particular in structure formation. It is a fundamental question to ascertain whether they also play a role in the matter-antimatter asymmetry, as proposed by the leptogenesis model. This question is related to the search for CP violating phenomena in the lepton sector. These considerations call for a deeper understanding of these particles, as a possible window on new phenomena.

Today, neutrino oscillations have been firmly established using solar, atmospheric, reactor, and accelerator neutrinos in a variety of experimental configurations, baselines and energies. A recent measurement [1] by the Daya Bay experiment (Fig. 1) gives a very clean graphical representation of this phenomenon, with a clear oscillatory pattern emerging.

These results have established the three neutrino Standard Model paradigm. In this paradigm, a central role is played by the Pontecorvo-Maki-Nakagawa-Sakata neutrino mixing matrix. This matrix $U$ relates the mass eigenstates $\nu_1$, $\nu_2$ and $\nu_3$ (with masses $m_1$, $m_2$ and $m_3$) to the flavour $f$ eigenstates $\nu_e$, $\nu_\mu$ and $\nu_\tau$ via

http://dx.doi.org/10.1016/j.nuclphysbps.2015.09.011

$\nu_f = \sum_i U_{fi}\nu_i$ where

$$\begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \times \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta_{CP}} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta_{CP}} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \quad (1)$$

with $c_{ij} = \cos\theta_{ij}$ and $s_{ij} = \sin\theta_{ij}$. In the case of Majorana neutrinos, additional CP violation parameters are present. The other relevant oscillation parameters are the squared mass splittings $\Delta m^2_{ij} = m^2_i - m^2_j$.

The precision on the parameters governing this matrix prior to this conference is shown in Table 1 [2]: the few percent precision level has been reached or will be soon reached, with the notable exception of the $\theta_{23}$ angle. Another unknown is the ordering of the mass states, that could either be $m_1 < m_2 < m_3$ (normal hierarchy) or $m_3 < m_1 < m_2$ (inverted hierarchy).

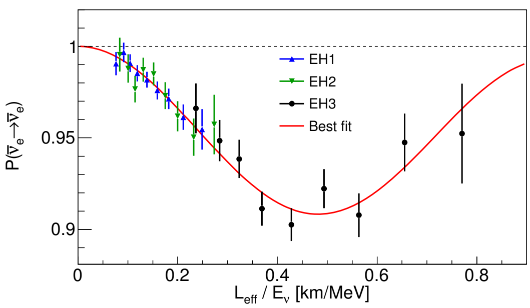


Figure 1: The electron antineutrino survival probability versus propagation distance $L$ over antineutrino energy $E_\nu$ as measured by the Daya Bay experiment [1].

Table 1: Precision on the neutrino mixing parameter [2] as obtained from a global fit to neutrino data, prior to ICHEP 2014.

| Parameter | Value | Precision (%) |
|---|---|---|
| $\Delta m^2_{21}$ | $7.5\ 10^{-5}$ eV$^2$ | 2.6 |
| $\theta_{12}$ | 34° | 5.4 |
| $\Delta m^2_{32}$ | $2.4\ 10^{-3}$ eV$^2$ | 2.6 |
| $\theta_{23}$ | 42° | 10 |
| $\theta_{13}$ | 9° | 8.5 |

In this review, we will show how all the more easily accessible transitions have been probed, namely $\nu_\mu \to \nu_\mu$ (as well as its CP conjugate), $\nu_\mu \to \nu_\tau$ and $\nu_\mu \to \nu_e$ with neutrino beams, and $\bar{\nu}_e \to \bar{\nu}_e$ with reactor antineutrinos. Moreover recent results are presented, mainly obtained with reactor and accelerator experiments, providing further improvements in the determination of several parameters and opening new experimental avenues.

The next steps in the study of neutrino oscillations are related to the following crucial questions and tasks:

- Is $\theta_{23}$ precisely equal to 45° ? Otherwise, in which octant does this angle lie?
- Is the neutrino mass hierarchy normal or inverted ?
- What is the value of the CP violation parameter $\delta_{CP}$ ?
- Perform precision tests of the PMNS paradigm (ideally at the % level, as for the CKM matrix)
- Are there any new neutrino states ?

Answering these questions will provide new information for model builders, help determine a possible symmetry between $\nu_\mu$ and $\nu_\tau$, and provide new input and plausibility for the theories of leptogenesis.

Several short baseline experiments (LSND, MiniBooNE, reactors, Ga source) have revealed anomalies that could be interpreted as due to oscillations with a $\Delta m^2 \simeq$ eV$^2$, that does not fit with the other mass splitting observed. No global satisfactory interpretation can be found because of tensions within the data [3], especially between appearance data and disappearance results. Most notably the goodness of fit of these global fits is very poor. An intense experimental effort, at accelerators (MicroBooNE), reactors and using intense sources (SOX) is ongoing to probe these anomalies, with first results expected in the next years.

## 2. Tau neutrino appearance

The disappearance of atmospheric neutrinos has been the first signal where the existence of neutrino oscillation has been established. In the standard PMNS paradigm this disappearance is related to the appearance of tau neutrinos, however indications of this process have so far not been conclusive.

The OPERA experiment has performed a search for $\nu_\mu \to \nu_\tau$ appearance with a baseline of 732 km (CERN to Gran Sasso) using the Emulsion Cloud Chamber technique. It has recently observed a fourth $\nu_\tau$ candidate [4] in the $\tau \to h$ decay channel (Fig. 2). In this search the total background has been evaluated to be $0.233 \pm 0.041$. The null hypothesis (no $\nu_\tau$ appearance) is excluded with a significance of 4.2 $\sigma$.