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 $\nu_{\mu} \rightarrow \nu_e$ 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
\[ \nu_f = \sum_i U_{fi} \nu_i \]

where

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

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).

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 \( \nu_\mu \rightarrow \nu_\tau \) 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 \( \tau \rightarrow h \) 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 \( \sigma \).

### 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 (%) |
|-----------|-------|---------------|
| \( \Delta m^2_{21} \) | \( 7.5 \times 10^{-5} \) eV\(^2\) | 2.6 |
| \( \theta_{12} \) | 34° | 5.4 |
| \( \Delta m^2_{32} \) | \( 2.4 \times 10^{-3} \) 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 \( \nu_\mu \rightarrow \nu_\mu \) (as well as its CP conjugate), \( \nu_\mu \rightarrow \nu_\tau \) and \( \nu_\mu \rightarrow \nu_\mu \) with neutrino beams, and \( \nu_\tau \rightarrow \nu_\tau \) 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 \( \Delta m^2 \approx eV^2 \), 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 \( \nu_\mu \rightarrow \nu_\tau \) 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 \( \tau \rightarrow h \) 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 \( \sigma \).
allowing a clean determination of $\theta_{13}$.

The detection technique is based on the inverse beta decay process $\bar{\nu}_e p \rightarrow e^+ n$. The signal is given by

$$P(\bar{\nu}_e \rightarrow \bar{\nu}_e) \approx 1 - \sin^2 2\theta_{13} \sin^2 \frac{\Delta m^2_{31} L}{4E}$$

allowing a clean determination of $\theta_{13}$.

The Daya Bay experiment has presented at this conference [6] the most precise determination of the $\theta_{13}$ mixing angle (Fig. 4)

$$\sin^2 2\theta_{13} = 0.084 \pm 0.005.$$  \hspace{1cm} (3)

as well as $|\Delta m^2_{ee}| = 2.4^{+0.10}_{-0.11} \times 10^{-3} \text{ eV}^2$, where $\Delta m^2_{ee}$ is defined by $\sin^2 \frac{\Delta m^2_{ee} L}{4E} = \cos^2 \theta_{12} \sin^2 \frac{\Delta m^2_{31} L}{4E}$.
Table 2: Main parameters of the running reactor neutrino experiments

| Parameter | DB | DC | RENO |
|-----------|----|----|------|
| n reactors | 6  | 2  | 6    |
| th. power (GW) | 17 | 8.5 | 16.5 |
| n det. | 8  | 2  | 2    |
| baseline min (m) | 363 | 400 | 290  |
| baseline max (m) | 1985 | 1050 | 1380 |
| live days | 621 | 460 | 794  |
| det. \(\nu\) | \(10^5\) | 17351 | \(10^6\) |

\[ \sin^2 \theta_{12} \sin^2 \frac{\Delta m^2 L}{4E} \]. This result is based on a data set four times larger (621 livedays) than the previously published result and provides an impressive precision of 6\% on \(\sin^2 \theta_{13}\). Over 1 million antineutrinos were detected, of which 150k are in the far detectors. The results from RENO (\(\sin^2 \theta_{13} = 0.101 \pm 0.013\)) [7] and Double Chooz (\(\sin^2 \theta_{13} = 0.090^{+0.032}_{-0.025}\)) [8] are in good agreement with the Daya Bay result, although with a significantly larger total uncertainty. The shape of the deficit induced by the neutrino oscillations agrees with the prediction from the near detectors extrapolated to the far detectors.

However, comparing both the measured positron spectrum and the derived antineutrino spectrum to the theoretical predictions, a distortion (“bump”), with an integral corresponding to a few percent of the total spectrum, was observed by Double Chooz [8], RENO[7] and Daya Bay [9] at an energy of around 5 MeV (Fig. 5). It is significant that all three experiments observe the same effect in the same energy range. The theoretical prediction is derived for \(^{235}\text{U},^{239}\text{Pu}\) and \(^{241}\text{Pu}\) from a measurement of their \(\beta\) spectrum at the ILL research reactor in the 1980. There, the positron spectrum was the primary measurement. The conversion from the positron to the antineutrino spectrum is done globally, since each of these spectra is composed of several thousands \(\beta\) decays branches: this conversion might introduce systematic uncertainties at the few \% level.

Preliminary studies disfavour background and energy-scale as an explanation of this discrepancy. According to preliminary studies the \(\theta_{13}\) measurement would not be affected thanks to the near detectors. A discussion on possible causes underlying this effect can be found for instance in [10] where discrepancies between the conversion method and \textit{ab initio} calculations of the antineutrino spectrum are pointed out.

Figure 4: Top: Measured positron energy spectrum of the Daya Bay far detectors [6] compared with the prediction from the near detectors in the no oscillation hypothesis (blue) and taking into account neutrino oscillation (red, best fit). Bottom: The ratio of measured and predicted spectra.

Figure 5: The black points show the ratio of the Double Chooz data [8], after subtraction of the background, to the non-oscillation prediction as a function of the visible energy of the prompt signal. The overlaid red line is the rate of the best-fit to the non-oscillation prediction with the reactor flux uncertainty (green) and the total systematic uncertainty (orange).

Clearly new studies in the coming years will be required to understand the origin of this distortion, studies which are necessary in order to reach the ultimate precision from reactor experiments both for the \(\theta_{13}\) measurements but also for possible investigations of new neutrino states.
4. Accelerator neutrino experiments

Long-baseline experiments using muon neutrino beams are sensitive to $\nu_\mu$ disappearance, which has the following approximate expression

$$P(\nu_\mu \rightarrow \nu_\mu) \approx 1 - 4 \cos^2 \theta_{13} \sin^2 \theta_{23} (1 - \cos^2 \theta_{13}) \times \sin^2 \theta_{23} \frac{\Delta m^2_{32} L}{4E}$$  (4)

for normal hierarchy, while for inverted hierarchy the relevant mass splitting is $\Delta m^2_{43}$, and to the $\nu_e$ appearance, governed by

$$P(\nu_\mu \rightarrow \nu_e) \approx \sin^2 2\theta_{13} \sin^2 \theta_{23} \frac{\Delta m^2_{32} L}{4E}$$
$$\sin 2\theta_{12} \sin 2\theta_{23} \frac{\Delta m^2_{23} L}{4E}$$
$$\sin^2 2\theta_{13} \sin^2 \theta_{23} \frac{\Delta m^2_{31} L}{4E} \sin \delta_{CP}$$  (5)

The disappearance channel provides sensitivity to the mixing angle $\theta_{23}$ and to the $\Delta m^2_{31}$ ($\Delta m^2_{43}$) mass splitting for the normal (inverted) hierarchy. Notice that there is no $\nu_e$ appearance for $\theta_{13} = 0$ (at least at this order, a much smaller appearance term exists related to the solar mass splitting $\Delta m^2_{21}$ and therefore with a much longer oscillation length). The appearance channel provides sensitivity to the mixing angle $\theta_{13}$ and its subleading terms to the CP violating phase $\delta_{CP}$. In the current phase of these experiments, the sensitivity is such that the results can start constraining the subleading terms as we will show.

4.1. MINOS

MINOS is a long-baseline experiment (735 km) from Fermilab to the Soudan mine, using a 5.4 kt magnetized iron/scintillator, on the NuMI beamline. MINOS has recently released a combined three flavour fit [11] to neutrino beam data (10.71 $10^{20}$ Protons-On-Target (POT)) antineutrino beam data (3.36 $10^{20}$ POT), MINOS+ and atmospheric neutrinos (Fig. 6). MINOS+ corresponds to a new phase of the project, with data being collected at a higher neutrino energy, on the same beam line at the same time as the NOvA experiment.

This analysis provides the most precise determination of the atmospheric mass splitting $|\Delta m^2_{43}|$:

$$|\Delta m^2_{43}| = 2.34^{+0.09}_{-0.07} 10^{-3} eV^2$$  (6)

$$\sin^2 \theta_{23} = 0.43^{+0.16}_{-0.04}$$  (7)

$$0.36 \leq \sin^2 \theta_{23} \leq 0.65 (90\% CL)$$  (8)

for the inverted hierarchy and

$$|\Delta m^2_{32}| = 2.34^{+0.09}_{-0.07} 10^{-3} eV^2$$  (9)

$$\sin^2 \theta_{31} = 0.43^{+0.16}_{-0.04}$$  (10)

$$0.37 \leq \sin^2 \theta_{23} \leq 0.64 (90\% CL)$$  (11)

for the normal hierarchy.

4.2. T2K

T2K is a long-baseline (295 km) neutrino experiment in Japan between J-PARC (Tokai) and Super-Kamiokande (SK). The primary proton beam with an energy of 30 GeV, a beam power of 235 kW, has provided 6.57 $10^{20}$ POT. This represents 8% of the final design exposure. The far detector is Super-Kamiokande with 22.5 kt fiducial mass and nearly 100% livetime.

The main features of the T2K experiment are:

- The use for the first time of an off-axis beam. This ensures that the flux has a narrow peak tuned to the first oscillation maximum. This feature minimizes the rate of high energy neutrinos whose interactions can produce background for the electron neutrino appearance search.
- The pion and kaon production by the interaction of 30 GeV protons on carbon has been measured by the NA61 experiment at CERN. This provides a good constraint for the determination of the beam flux.
- The excellent particle identification capabilities in Super-Kamiokande. The $\mu \rightarrow e$ misidentification is at the 1% level. This allows to cleanly distinguish $\nu_e$ from $\nu_\mu$ interactions.

Figure 6: MINOS reconstructed energy spectrum for $\nu_\mu$ and $\bar{\nu}_\mu$ samples and the zenith angle distributions for atmospheric neutrinos. The red histogram shows the no oscillations distribution and the black histogram the best fit.
T2K has a sophisticated set of near detectors measuring neutrino interactions at 280 m from the target [12]. These measurements allow to significantly reduce the flux and cross-section systematic uncertainty down to 7% (Fig. 7).

The selection used for the far detector in the $\nu_\mu$ disappearance analysis is based on one-ring $\mu$-like events. The sample selected in this way is shown in Fig. 8: it consists of 120 events while 446 ± 23 (syst.) events are expected in the case of no oscillation, showing muon neutrino disappearance in a dramatic way. The best fit [13] is close to the point of maximum mixing $\theta_{23} = \pi/4$ and the allowed region provides the best constraint on the $\theta_{23}$ value (Fig. 9). The 1D 68% confidence intervals are $\sin^2(\theta_{23}) = 0.514^{+0.055}_{-0.056}$ ($0.511 \pm 0.055$) and $\Delta m^2_{32} = 2.51 \pm 0.10$ ($\Delta m^2_{13} = 2.48 \pm 0.10$) $\times 10^{-3} \text{eV}^2/c^4$ for the normal hierarchy (inverted hierarchy). The T2K neutrino interaction generator, NEUT, includes an effective model (pionless $\Delta$ decay) that models some but not all of the expected multinucleon cross section. The impact of possible multinucleon effects in neutrino interactions has been studied in more detail. The mean biases in the determined oscillation parameters are less than 1% for the ensemble, though the $\sin^2(\theta_{23})$ biases showed a 3.5% rms spread.

The search for a signal of $\nu_e$ appearance yields a sample of 28 events (Fig.10) in the far detector while the background, in the case of no appearance, is evaluated to be 4.9±0.6 (syst.) events. The dominant contribution to the background is given by the intrinsic $\nu_e$ in the beam. Their flux has been measured in the near detector to be $1.01 \pm 0.10$ with respect the prediction [12]. This gives 7.3 $\sigma$ evidence of a non-zero $\theta_{13}$ angle [15] and constitutes the first direct observation of the appearance observes.
of a new neutrino flavour.

Figure 10: The reconstructed energy distribution for T2K $\nu_e$ candidate events [15] in the far detector with the MC prediction at the best fit of $\sin^2 2\theta_{13} = 0.144$.

Figure 11 shows for each value of $\delta_{CP}$ the one dimensional allowed interval for $\sin^2 2\theta_{13}$. By comparing these intervals to the value measured by the reactors experiments, it is possible to derive allowed regions for $\delta_{CP}$. For instance, especially for the case of inverted hierarchy, the values around $\delta_{CP} \approx \pi/2$ are disfavoured.

In T2K, a combined fit [16] using the $\nu_\mu$ disappearance and $\nu_e$ appearance samples has been conducted. This study takes advantage of the fact that the appearance and disappearance probabilities shown in Eq. 6 and Eq. 9 depend on the same parameters set, if the subleading terms are taken into account. Moreover, from an experimental point of view, there are some correlated systematic uncertainties that are best taken into account in this kind of combined fit rather than in an external fit, where only an approximate (or none at all) treatment of these effects is possible. The results of this fit are shown in Fig. 12. Using the measurement of $\theta_{13}$ done by reactor experiments, the excluded regions for $\delta_{CP}$ at the 90% CL are [0.146,0.825]$\pi$ ([-0.080,1.091]$\pi$) for normal (inverted) mass hierarchy.

The best fit point is obtained for a value very close to $\delta_{CP} = -1/2\pi$. Of course this is only a very preliminary hint that will need much more data to become a firmly established experimental result. However, a few points can be made already now. First, if nature has chosen the value $\delta_{CP} = 3/2\pi$ CP violation effects are maximal and therefore relatively easy to detect. We can also notice that this solution satisfies the leptogenesis bound [17] $|\sin \theta_{13} \sin \delta_{CP}| \geq 0.11$ with no additional source of CP violation.

T2K has recently resumed data-taking in the anti-neutrino mode and more results in this field are expected.

Figure 11: The T2K 68% and 90% CL allowed regions for $\sin^2 2\theta_{13}$, as a function of $\delta_{CP}$ assuming normal hierarchy (top) and inverted hierarchy (bottom) [15]. The solid line represents the best fit $\sin^2 2\theta_{13}$ value for given $\delta_{CP}$ values. The shaded region shows the average $\theta_{13}$ value from the PDG2012.

Figure 12: $\Delta \chi^2$ as a function of $\delta_{CP}$ obtained by a global analysis of T2K data [16], combining appearance and disappearance samples and the measurement of $\theta_{13}$ by the reactor experiments. The horizontal lines show the critical value $\Delta \chi^2$ corresponding to a confidence level of 90%. The blue and gray bands indicate the 90% CL excluded regions.
4.3. NOvA

NOvA is an off-axis experiment from Fermilab to Ash River (810 km) on the NuMI beam line. Its far detector is a 14 kt totally active structure filled with liquid scintillator. The first neutrino events have been observed this year. The physics goals of NOvA are similar to those of T2K, that is a study of $\nu_e$ appearance with a long baseline, in order to study CP violation effect. Given the much longer baseline, NOvA will also have some sensitivity to the neutrino mass hierarchy through matter effects. NOvA has recently started data-taking and first results are expected in 2015.

5. Conclusions

The study of neutrino oscillations has provided many surprising discoveries in the last 15 years, establishing the three neutrino mixing paradigm, implying physics beyond the SM. The field is approaching the few % precision era due to dedicated experimental efforts. The experiments begin to be sensitive to CP violation via the interplay of accelerator and reactor observables. Major efforts are ongoing towards answering the remaining open questions and providing precision tests.

For the long-baseline accelerator experiments, recent studies are focussed on the LBNO project in Europe, LBNF in USA and Hyper-Kamiokande in Japan with different baselines and technologies. The full exploration of the PMNS matrix and in particular of the CP-violating parameter $\delta_{CP}$ will require the construction of at least one of this experiments in the next decade.

Acknowledgements

The results presented here have been obtained by many collaborations devoted to the study of neutrino properties in a variety of experiments: OPERA, Super-Kamiokande, Daya Bay, RENO, Double Chooz, MINOS, T2K, NOvA, ... I would like to thank the speakers of the parallel session for feedback and for providing plots and information while preparing this talk and this report.

References

[1] F. An et al. (Daya Bay Collaboration), Phys. Rev. Lett. 112, 061801 (2014).
[2] F. Capozzi et al., arXiv:1312.2878. See also M. Tortola, these proceedings.
[3] J. Kopp et al., arXiv:1303.3011v3.
[4] M. Komatsu, these proceedings. N. Agafonova et al. (OPERA Collaboration), arXiv:1407.3513v2.
[5] K. Abe et al. (Super-Kamiokande collaboration), Phys. Rev. Lett. 110, 181802 (2013).
[6] W. Wang, these proceedings.
[7] S. Seo, talk given at the NEUTRINO 2014 conference.
[8] Y. Abe et al. (Double Chooz collaboration), arXiv:1406.7763.
[9] W. Zhong, these proceedings.
[10] D. Dwyer and T. Langford, arXiv:1407.1281.
[11] P. Adamson et al. (MINOS Collaboration), Phys. Rev. Lett. 112, 191801 (2014).
[12] A. Hillairet, these proceedings.
[13] K. Abe et al. (T2K Collaboration), Phys. Rev. Lett. 112, 181801 (2014).
[14] A. Himmel (Super-Kamiokande Collaboration), arXiv:1310.6677.
[15] K. Abe et al. (T2K Collaboration), Phys. Rev. Lett. 112, 061802 (2014).
[16] L. Escudero, these proceedings.
[17] S. Pascoli et al., Nucl. Phys. B 774, 1 (2007).