Chapter 1

Neutrino Masses and Mixing: Experimental Results

Marco Zito
zito@dapnia.cea.fr

Dapnia-SPP, CEA-Saclay,
91191 Gif-sur-Yvette Cedex, France

Abstract A review of experimental results in the domain of neutrino masses and mixing is presented, stressing the important theoretical and experimental progresses achieved in the last years as well as the open questions for the future experiments.

1.1 Introduction

In this review of experimental neutrino physics we will present the recent results, with special attention to the domain of the neutrino oscillations. In the second part we will present the open questions and the experimental program to provide an answer to these.

Since its discovery, many experiments have tried to detect the neutrino mass, either directly or through oscillation measurements. The study of neutrinos from the sun and those produced by the interaction of cosmic rays in the atmosphere have played a crucial role. In the recent years, experiments with reactor and accelerator neutrinos have confirmed the spectacular findings in this sector.

To introduce the measurement of neutrino oscillations, let us summarize that the flavor eigenstates are in general linear combination of the mass eigenstates, the two basis being connected by a unitary mixing matrix. In the case of three neutrino families the mixing matrix, called Pontecorvo-Maki-Nakagawa-Sakata (PMNS) matrix, can be written

$$U = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{pmatrix} \times \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \quad (1.1)$$

where $c_{ij} = \cos(\theta_{ij})$, $s_{ij} = \sin(\theta_{ij})$, θ_{ij} are mixing angles and δ is a CP violating phase. If the neutrinos are of Majorana type, there are 2 additional phases and the PMNS matrix U gets multiplied by diag(1,$e^{i\alpha_1}$,$e^{i\alpha_2}$).

For two neutrino oscillations, the appearance probability of neutrino of flavor β in a beam of neutrino flavor α is given by

$$\mathrm{Prob}(\alpha \to \beta) = \sin^2 2\theta \sin^2(\frac{\Delta M^2_{21} L}{4p}) \quad (1.2)$$

where p is the neutrino momentum, $\Delta M^2_{21} = M^2_2 - M^2_1$, $M_{1,2}$ are the two mass eigenvalues and L is the distance from the neutrino source to the detector.

1.2 Solar Neutrinos

The sun is a very bright source of neutrinos with the spectrum shown in Fig. 1.1. For several decades, many experiments have probed the flux of solar neutrinos. Their findings are summarized in Fig. 1.2: a deficit of solar neutrinos is observed with respect to the predictions. This deficit depends on the fraction of the neutrino flux probed by the experiment.

Two recent experiments played a crucial role in this field: SuperKamiokande and SNO. SuperKamiokande is a large underground water Cherenkov detector, comprising 50 kton pure water and 11146 large PMT. It is sensitive to solar neutrino down to about 6 MeV. Besides confirming the solar neutrino deficit, its data [1] allowed to constrain other important effects like spectral distortions and day-night variations due to a possible neutrino regeneration in the earth.

SNO is a water Cherenkov detector consisting of 1000 tonnes of heavy water (D_2O) in the Sudbury mine. It is sensitive to the following reactions:

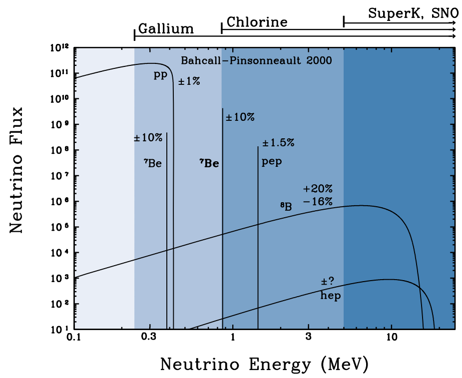

Figure 1.1: Spectrum of solar neutrinos produced by different processes according to the standard solar model from http://www.sns.ias.edu//~jnb.

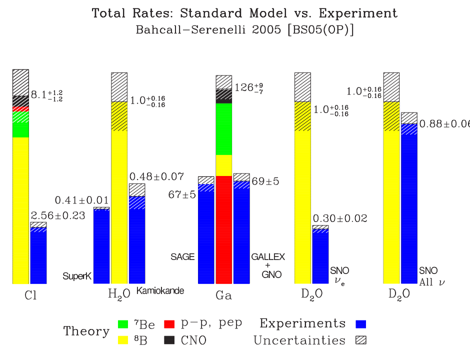

Figure 1.2: Standard Solar Model expectations (highest bars) and data (blue bars) for the observation of the solar neutrino flux from http://www.sns.ias.edu//~jnb.

- Electron Scattering (ES): $\nu_x + e^- \to \nu_x + e^-$ mainly sensitive to ν_e.
- Charged Current (CC): $\nu_e + d \to p + p + e^-$ that provide a good measurement of the ν_e flux and spectrum.
- Neutral Current (NC): $\nu_x + d \to p + n + \nu_x$ that provides an equal cross section for all ν types and therefore measure the total ^8B ν flux from the sun.

Through these reactions, SNO has a unique sensitivity to ν_e and to all active neutrino flavors $\nu_e + \nu_\mu + \nu_\tau$.

The SNO measurement [2] (Fig.1.3) of the neutrino fluxes Φ_{CC} and Φ_{NC}

$$\frac{\Phi_{CC}}{\Phi_{NC}} = \frac{\Phi_{\nu_e}}{\Phi_{\nu_e} + \Phi_{\nu_\mu} + \Phi_{\nu_\tau}} = 0.34 \pm 0.023(stat)^{+0.029}_{-0.031} \tag{1.3}$$

provides an extremely clear and compelling proof of neutrino flavor transformation.

These results were nicely confirmed and complemented by KamLAND, measuring antineutrinos produced by nuclear reactors in Japan. Kamland [3] provided a very clean confirmation of "solar" neutrino oscillation (Fig. 1.4). KamLAND results were crucial in the precise measurement of mass difference involved in these oscillations. The established explanation of the solar ν deficit is the MSW effect [4] taking place in the sun.

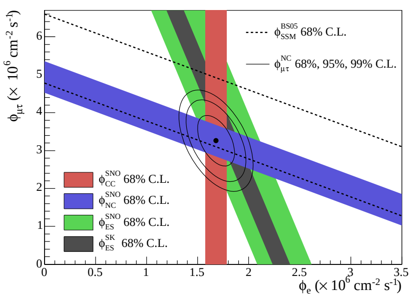

Figure 1.3: SNO and SK Data. Flux of $\mu + \tau$ neutrinos versus flux of electron neutrinos. CC, NC and ES flux measurements are indicated by the filled bands. The total solar neutrino flux predicted by the Standard Solar Model is shown as dashed lines.

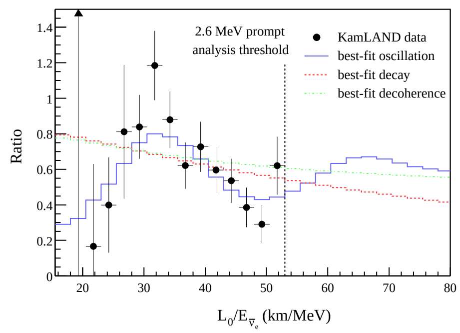

Figure 1.4: KamLAND data. Ratio of the observed electron antineutrino spectrum to the expectation for no-oscillation versus L_0/E. The curves show the expectation for the best-fit oscillation, best-fit decay and best-fit decoherence.

1.3 Atmospheric Neutrinos

High energy cosmic rays (mainly protons) interact in the atmosphere and produce hadronic showers, with abundant pion production. The pions decay producing a ratio of ν_μ to ν_e close to 2. Since the 80's, underground experiments (IMB, Soudan, Kamiokande) measuring these neutrinos gave indications of an anomaly, measuring a ratio $N(\nu_\mu)/N(\nu_e)$ much lower than expected.

The real step forward in this domain came with the data of SuperKamiokande [5], with a large fiducial mass, excellent electron/muon separation and good neutrino direction reconstruction. This allowed the study of the muon neutrino deficit versus the zenithal angle (Fig. 1.5). For multi-GeV events, there is no deficit for downward ν_μ ($cos\Theta = 1$) while there is a strong deficit for upward ν_μ ($cos\Theta = -1$). This is explained by the large difference of the path length: 10 km for downward versus 12 000 km for upward ν. The data indicate that this mixing angle is close to maximal ($\theta \simeq \pi/4$). The squared-mass difference ΔM^2 extracted from these atmospheric neutrino oscillations is much larger than the squared-mass difference implied by solar neutrino data.

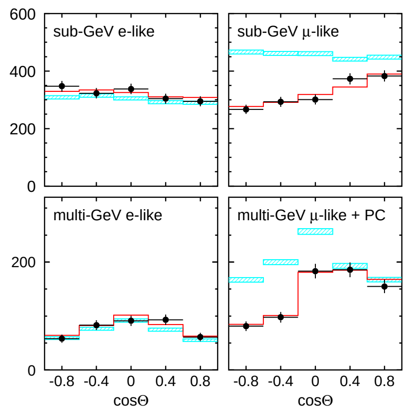

Figure 1.5: SuperKamiokande atmospheric ν data. The zenith angle distribution for sub-GeV and multi-GeV e-like and μ-like events. The hatched area shows the prediction for the no oscillation hypothesis.

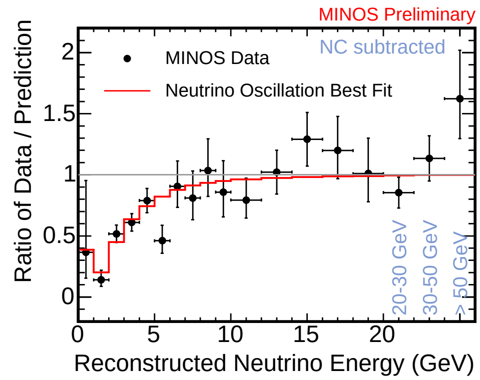

Figure 1.6: Ratio of the spectrum of the MINOS far detector spectrum to the null oscillation prediction (points) with the best-fit oscillation expectation overlaid (red).

1.4 Recent results from MINOS

Two accelerators experiments, K2K and MINOS, have probed ν_μ oscillation at the atmospheric ΔM and have provided conclusive evidence of ν_μ disappearance. MINOS is a long baseline neutrino oscillation experiment using the intense NuMI neutrino beam produced using the Fermilab Main Injector. It consists of two magnetized iron and scintillator detectors: a 0.98 kton Near Detector located 1 km downstream of the target and a 5.4 kton Far Detector in the Soudan Underground Laboratory at 735 km from the ν source. Results [6] have been presented recently using data from 2005 to 2007 for a total exposure of 2.5 10^{20} POT. 563 neutrino-like events satisfying the criteria for Charged Current interaction have been selected in the Far Detector where 738 ± 30 are expected in the absence of oscillations. A combined analysis of the near and far detector data is performed assuming two-flavor $\nu_\mu \to \nu_\tau$ oscillations. A clear signal of ν_μ disappearance is provided and the measured neutrino squared-mass difference and mixing angle are

$$\Delta m^2_{32} = (2.38 \, ^{+0.20}_{-0.16}) \times 10^{-3} \mathrm{eV}^2/c^4 \quad (1.4)$$

$$\sin^2(2\theta_{23}) \quad > \quad 0.84 \text{ at } 90\% CL. \tag{1.5}$$

1.5 Are there sterile neutrinos ?

The data from the LSND experiment [7] gave a hint of a neutrino oscillation at $\Delta m^2 \simeq 1$ eV$^2/c^4$. This would have been an indication of a fourth neutrino mass state. MiniBooNE [8] uses neutrinos produced by the Fermilab Booster, with the neutrino energy peaking at 700 MeV. The MiniBooNE detector is situated at 541 m from the target and consists of a sphere of 800 tons of mineral oil instrumented by 1280 8" PMTs. The primary analysis is the search for $\nu_\mu \to \nu_e$ oscillations with $\Delta m^2 \simeq 1$eV$^2/c^4$. Background to this analysis are constrained with *in situ* measurements and cross checks. The neutrino energy E_ν of the signal candidates is shown in Fig. 1.7. In the analysis region $475 < E_\nu < 3000$ MeV, 380 events are observed where the expected background is $355 \pm 19(stat) \pm 35(sys)$. The 90 % confidence level limits on the $\nu_\mu \to \nu_e$ oscillation parameters are shown on Fig.1.8. The MiniBooNE yields no evidence for neutrino oscillation. An excess of energy below the analysis threshold of 475 MeV remains under investigation.

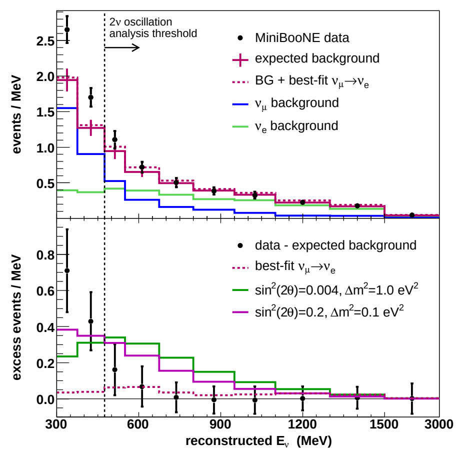

Figure 1.7: Spectrum of neutrino energy for candidate events in MiniBooNE (top) with the expected background and background subtracted spectrum (bottom). No significant excess is observed in the analysis region $475 < E_\nu < 3000$ MeV.

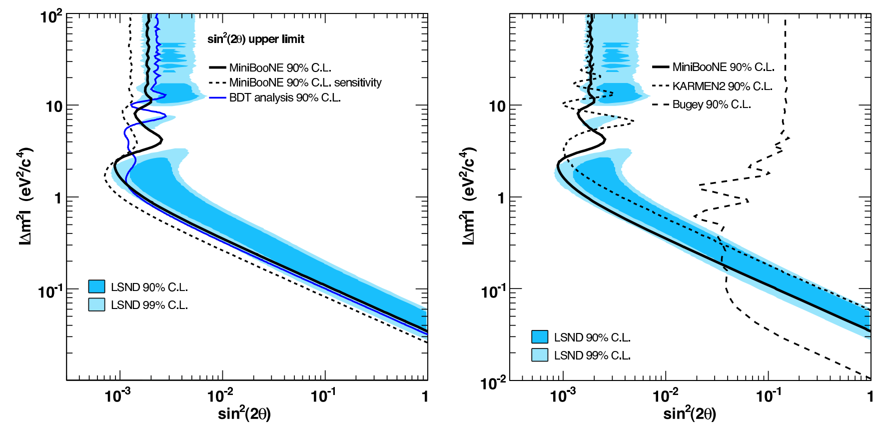

Figure 1.8: The left plot shows MiniBooNE 90% CL limit (thick solid curve) and sensitivity (dashed curve). The right plot shows the limits from the Karmen and Bugey experiments and the allowed regions from the LSND experiment.

1.6 PMNS today and Open Questions in Neutrino Physics

The evidence for neutrino oscillation has far reaching consequences and imply that neutrinos have non zero mixing angles and tiny but non-zero masses. Moreover the lepton flavor is not conserved. Our current knowledge about the neutrino mass and mixing is summarized in the following results from a global fit [9] to solar, atmospheric, reactor and accelerator experiments (MINOS data were not included in this fit):

$$\begin{aligned}
\Delta m_{21}^2 &= 7.92\ (1 \pm 0.09)\ 10^{-5} eV^2/c^4 \\
\sin^2\theta_{12} &= 0.314\ (1^{+0.18}_{-0.15}) \\
\Delta m_{atm}^2 = \frac{1}{2}(\Delta m_{31}^2 + \Delta m_{32}^2) &= 2.4\ (1^{+0.21}_{-0.26})\ 10^{-3} eV^2/c^4 \\
\sin^2\theta_{23} &= 0.44\ (1^{+0.41}_{-0.22}) \\
\sin^2\theta_{13} &= 0.9\ (1^{+2.3}_{-0.9}) 10^{-2}
\end{aligned} \qquad (1.6)$$

The oscillation data are sensitive only to mass differences, therefore the absolute value of the neutrino masses is still unknown. Moreover, the sign of Δm_{atm}^2 is not known. This leaves open the important question whether ν_3 is the heaviest (normal hierarchy) or the lightest (inverted hierarchy) of the three mass states. Despite the spectacular progress of experimental investigations in these field, several fundamental questions remains open:

- What are the values of the neutrino masses ?
- Are the neutrinos of Dirac or Majorana type ?
- What is the neutrino mass hierarchy, normal or inverted ?
- What is the value of the mixing angle θ_{13} ?
- Is there CP violation in the leptonic sector ?

In the following sections we will see how a rich experimental program is progressing towards an answer to these difficult but extremely important questions.

1.7 The Mass and the Nature of the Neutrino

The measurement of the neutrino mass is a long and still unfinished effort, starting in the 30's when Fermi showed how a massive neutrino would distort the beta decay spectrum of the electron near the end point. KATRIN is an ambitious experiment aiming at refining the current limit ($m_\nu < 2.2$ eV) from the Mainz and Troitsk experiments [10]. Studying tritium beta decays, it aims at a sensitivity of 0.2 eV and will start taking data in 2010. Other projects like MARE will also explore this field with different techniques. Given the very small energy scale involved, laboratory measurement of the neutrino mass are very difficult. Today the best limit comes from cosmology [11].

A related experimental effort is focussing on the search for neutrinoless double beta decay violating lepton number by two units. The best sensitivity has been obtained by the Heidelberg-Moscow ^{76}Ge experiment, with a controversial claim of observation [12]. Other experiments like NEMO3 or Cuoricino have upper limits on $|\langle m_\nu \rangle|$ slightly below the eV level. A large number of projects (CUORE, GERDA, EXO, Super-NEMO, etc.) have been launched to tackle the problem of reducing the background that it is the limiting factor. A variety of solutions - cryogenic detectors, ultra-pure materials, high resolution, TPC - are considered. The aim is to push the sensitivity down to 0.01 - 0.05 eV, with the capability to probe the inverted hierarchy scenario.

1.8 The Last Oscillation Channel

Similar to what happen in the quark sector, CP violation effects due to the phase δ of the PMNS matrix are proportional to the Jarlskog invariant $J \propto \sin\theta_{23}\sin\theta_{13}\sin\theta_{12}$. Therefore, it is necessary to establish that the mixing angle θ_{13} is different from zero before proceeding to the more difficult measurement of CP violation in the leptonic sector.

θ_{13} can be probed by looking at the disappearance of electron antineutrino produced by a nuclear reactor. Several experiments like Double-Chooz and Daya Bay are following this approach. The experimental effect is less than 10 %. The greatest sensitivity is reached by using two or more identical detectors at different distances from the reactor core. Several systematics like the reactor flux, the detection efficiency etc., cancel taking the ratio of the signals in the two detectors.

The T2K experiment is a long baseline neutrino experiment with a powerful proton beam (0.75 MW) producing a ν_μ beam. θ_{13} can be probed searching for ν_e appearance in SuperKamiokande, the far detector, at 295 km from the beam source. The combination of distance L and energy corresponds to the first maximum of the "atmospheric" oscillation. A magnetized detector (Fig. 1.9) at 280 m from the proton target will precisely characterize the neutrino beam and its interactions. T2K will start taking data in 2009 and will provide the best sensitivity [13] to θ_{13} at the beginning of the next decade (Fig. 1.10).

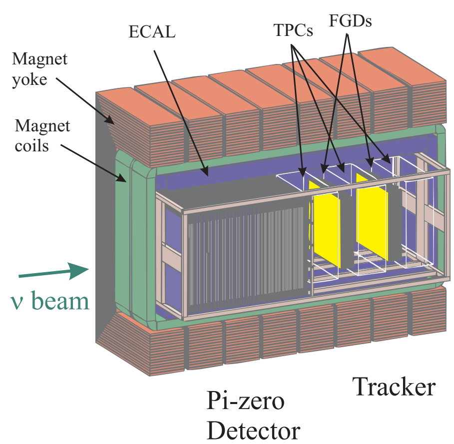

Figure 1.9: The near detector of the T2K experiment at 280m from the proton target.

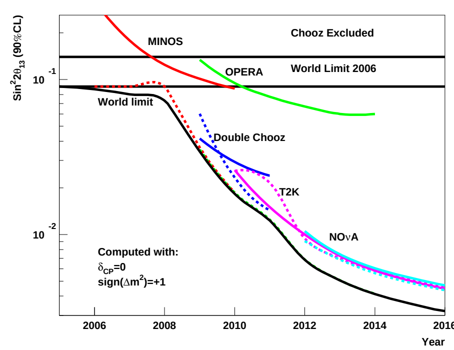

Figure 1.10: Sensitivity to $\sin^2 2\theta_{13}$ as a function of time for various experiments.

1.9 Towards CP Violation in the Lepton Sector

The next generation of neutrino accelerators and experiments is under study in order to test CP violation in the neutrino sector using beams of neutrinos and antineutrinos. Several accelerator facilities are under consideration: the Superbeam is a very intense (4MW) proton beam with a baseline of ~ 100 km and with a Megaton class detector as the far detector. In a Betabeams beta decaying ions are accelerated to produce a very pure ν_e and $\overline{\nu_e}$ beam. In a Neutrino Factory muons are accelerated and then decay in long straight sections to produce at the same time a ν_μ and $\overline{\nu_e}$ beams. The study of the feasibility of these projects and their physics reach is the object of detailed studies in USA, Japan and Europe.

1.10 Conclusion and prospects

The last decade has witnessed spectacular progress in neutrino physics with the discovery of neutrino masses and mixings through oscillations, their confirmation with reactor and accelerator experiments and a large improvement in precision of the measurements. We are today in the exciting phase of preparation of a new round of experiments. Their goal is to provide answers to fundamental questions, like the nature of this particle and the existence of CP violation in the leptonic sector.

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