RECENT MEASUREMENTS OF θ_{13} MIXING ANGLE IN NEUTRINO OSCILLATION EXPERIMENTS*

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This article presents recent developments in neutrino experimental physics associated with θ_{13} oscillation mixing angle measurements. Latest results from reactor (Daya Bay, Reno, Double Chooz) and long baseline (T2K, MINOS) experiments are presented.

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1. Introduction

Since the existence of neutrino oscillation phenomenon (*i.e.* periodic transformation of flavour during propagation) has been proved, lots of experiments observed oscillations of neutrinos of all flavours and in a broad range of energies. In a simple, 2-flavour scheme, when we assume that observable flavour eigenstates (ν_e, ν_μ *etc.*) are a mixing of mass eigenstates (ν_1, ν_2), a probability of neutrino oscillation can be expressed with following formula

$$P = \sin^2(2\theta)\sin^2\left(1.27\,\Delta m^2 L/E\right) ,$$

where L (expressed in km) is distance travelled by neutrinos and E (expressed in GeV) is neutrino energy. θ (mixing angle) and Δm^2 (difference of masses squared of mass eigenstates involved, expressed here in eV^2) are parameters of nature (to be determined in the experiments). It is now a widely accepted fact that what we observe can be described in a framework of 3-flavour oscillations, where observable flavour eigenstates (ν_e, ν_μ, ν_τ) are a result of mixing of mass eigenstates (ν_1, ν_2, ν_3) with a mixing matrix

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(called Maki–Nakagawa–Sakata) that can be parametrised in the following way

$$\begin{pmatrix}\nu_e\\ \nu_\mu\\ \nu_\tau\end{pmatrix}=\begin{pmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-\mathrm{i}\delta}\\ -s_{12}c_{23}-c_{12}s_{13}s_{23}e^{\mathrm{i}\delta} & c_{12}c_{23}-s_{12}s_{13}s_{23}e^{\mathrm{i}\delta} & c_{13}s_{23}\\ s_{12}s_{23}-c_{12}s_{13}c_{23}e^{\mathrm{i}\delta} & -c_{12}s_{23}-s_{12}s_{13}c_{23}e^{\mathrm{i}\delta} & c_{13}c_{23}\end{pmatrix}\begin{pmatrix}\nu_1\\ \nu_2\\ \nu_3\end{pmatrix} ,$$

where $c_{ij} \equiv \cos\theta_{ij}$ and $s_{ij} \equiv \sin\theta_{ij}$ (for $ij = 12, 13, 23$) are three mixing angles and δ is a CP violation phase. The mass spectrum is defined by two differences of masses squared measured in oscillation experiments: Δm^2_{23} obtained in *atmospheric* experiments (small L/E) and Δm^2_{12}, almost three orders of magnitude smaller, obtained in *solar* experiments (with large L/E).

θ_{13} was the last unknown mixing angle. It was difficult to measure because effects that can be used to estimate it (excesses or deficits of certain flavours of neutrinos) are very small. However, θ_{13} is a very important parameter — we are able to study CP violation and matter effects (the latter can be used to determine neutrino mass hierarchy) in neutrino oscillations only if it is non-zero.

The θ_{13} can be studied in two ways. One is by observing the electron antineutrino disappearance in reactor experiments. These experiments detect low energy $\bar{\nu}_e$ (their energy is of the order of a few MeV) produced in beta decays of radioactive elements in nuclear power plants. The effects of oscillations can be observed for baselines of the order of 1 km. Typically, one builds a near detector, close to reactors, to study unoscillated beam, and a far one, a kilometer away to see effects of oscillations. The existence of a near detector allows to minimize systematic errors, including flux uncertainty. The probability for this process is the following (only leading term is presented)

$$P_{\bar{\nu}_e\to\bar{\nu}_e} = 1 - \sin^2(2\theta_{13})\sin^2\left(1.27\,\Delta m^2_{13}L/E\right) .$$

Alternatively, one can observe muon neutrino oscillations into electron neutrino (by looking at ν_e appearance) in long baseline experiments with artificial ν_μ beams. The typical beam energies are a few GeV, and distances hundreds of kilometers. Here again, building the near along with the far detector is advisable. The probability for this mode of oscillations is the following (only leading term is presented)

$$P_{\nu_\mu\to\nu_e} = \sin^2(2\theta_{13})\sin^2(\theta_{23})\sin^2\left(1.27\,\Delta m^2_{23}L/E\right) .$$

A dependence on θ_{23} is visible; also, the subleading terms in the above formula depend on mass hierarchy and δ_{CP}. Determining the value of θ_{13} is, therefore, more difficult in the case of the latter measurement.

2. Reactor experiments (Daya Bay, Reno, Double Chooz)

The most important neutrino oscillation experiment studying the disappearance of reactor $\bar{\nu}_e$ to determine θ_{13} is Daya Bay [1]. Located in southern China, in the vicinity of two nuclear power plants Daya Bay and Ling Ao, it consists of two near and one far station. The near stations measure non-oscillated flux of neutrinos from the reactors, the far station probes the flux after oscillations occurred. The results presented here correspond to the data collected with 3 antineutrino detectors (ADs) in the near stations and 3 in the far one. An AD, shown in Fig. 1, is composed of three nested cylindrical volumes separated by concentric acrylic vessels. The innermost volume holds 20 t of liquid scintillator doped with gadolinium and serves as the antineutrino target. The middle volume is called the gamma catcher and is filled with 20 t of un-doped liquid scintillator for detecting gamma-rays that escape the target volume. The outer volume contains 37 t of mineral oil to provide the optical homogeneity and to shield the inner volumes from radiation originating from the container. Scintillation signals are collected by 192 photomultipliers. The ADs are immersed in a water Cherenkov detector — a water container equipped with photomultipliers — to monitor muons that

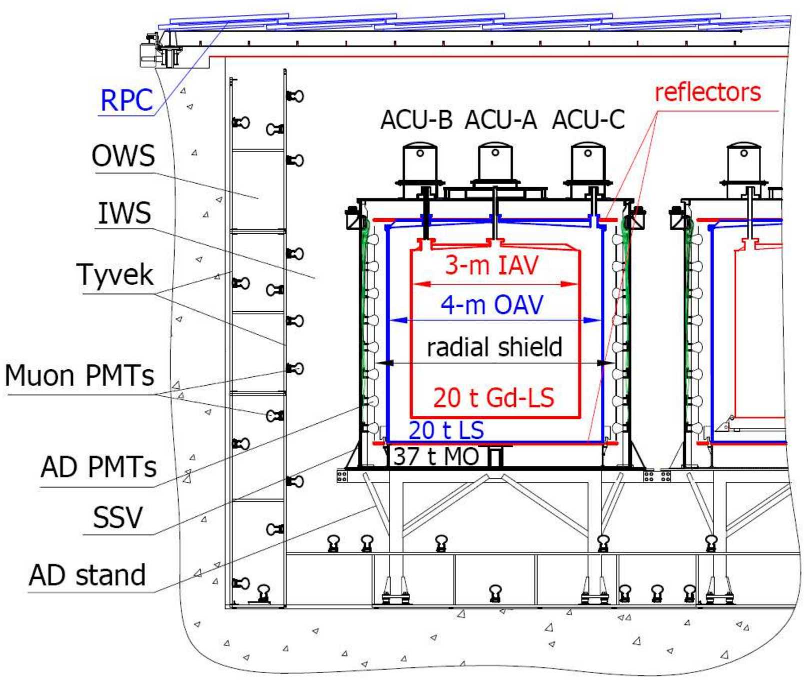

Fig. 1. Schematic view of a Daya Bay detection module. Picture taken from [1].

can produce spallation neutrons, attenuate gamma rays from surroundings and moderate neutrons. The principle of detection is based on inverse beta decay (IBD) process: $\bar{\nu}_e + p \to e^+ + n$. An event is detected when a coincidence is observed: prompt signal from the positron and delayed signal from neutron capture on Gd.

By comparing rates of events observed in the near and far detectors, with all necessary corrections, one can see effects of oscillations (see Fig. 2). Daya Bay experiment determined the far to near ratio of observed events $R = 0.944 \pm 0.007(\mathrm{stat.}) \pm 0.003(\mathrm{syst.})$ which can be translated into the final result: $\sin^2(2\theta_{13}) = 0.089 \pm 0.010(\mathrm{stat.}) \pm 0.005(\mathrm{syst.})$ [1] (hypothesis of no oscillations is excluded at the level of 7.7σ). A more advanced analysis was also performed taking into account not only rate but also energy spectrum of antineutrinos. Its result is even more precise than for the rate only analysis [2]. Daya Bay currently measures θ_{13} with the best precision among all experiments. The measurement is statistics limited, and since the experiment is constantly taking data, total uncertainty of the results is expected to further decrease.

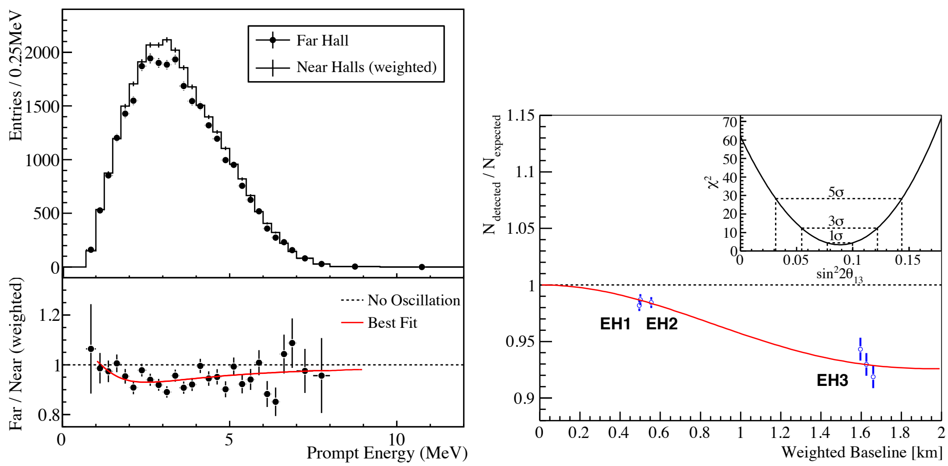

Fig. 2. Daya Bay results. Left: measured prompt energy spectrum of the far hall compared with the no-oscillation prediction based on the measurements of the two near halls along with the ratio of the two. Right: ratio of measured *versus* expected signals in each detector, assuming no oscillation and the result of fit in the inset. Pictures taken from [1].

Two other reactor experiments involved in θ_{13} measurements are Korean RENO [3] and French Double Chooz [4]. They report results with larger systematic uncertainties than Daya Bay, however some improvements are expected.

3. Long baseline experiments (T2K, Minos)

The experiment that first indicated a possibility (2.5σ) of non-zero θ_{13} is Tokai2Kamioka (T2K), a long baseline experiment located in Japan. Its artificial narrow band ν_μ beam is created in J-PARC laboratory in Tokai, on the east coast of Honshu and aims at Super-Kamiokande, a large water Cherenkov detector situated in the Japanese Alps in the Gifu prefecture, 295 km away from Tokai. The near detector is installed 280 m from the target. The experiments' main goals are studying muon neutrino disappearance and electron neutrino appearance.

To produce neutrinos, high energy proton beam hits graphite target; emerging hadrons (mainly pions) are collimated by three magnetic horns and decay into muon neutrinos: $\pi^+ \to \mu^+ + \nu_\mu$. Resulting beam is composed mostly of ν_μ, with small admixtures of $\bar{\nu}_\mu$ and ν_e produced in decays of muons and kaons. The detectors are placed slightly off-axis to achieve favourable spectrum shape with a peak around 0.6 GeV, where the first oscillation maximum is located.

The near detector (ND280) is a set of subdetectors aimed at precise reconstruction of tracks produced in neutrino interactions. The core of the CC event selection is based on the tracker region, which consists of two Fine Grained Detectors (FGDs), that constitute active target for neutrino interactions and enable one a reconstruction of vertices and short tracks (mainly protons). FGDs are supplemented with three gas Time Projection Chambers (TPCs), capable of identifying (using energy loss patterns) long tracks like muons and determining their charge and momentum (using tracks' curvature in magnetic field). ND280 monitors unoscillated beam, estimates ν_e contamination, measures ν_μ spectrum (by analysing CCQE interactions, where observation of a produced charged lepton can easily be translated to the energy of incident neutrino). It is also needed for cross-section determination. All these measurements are important steps towards minimisation of systematic errors. ND280 plays the crucial role in oscillation analyses: it constrains flux estimates and cross-section parameters. External constraints are also obtained from NA61/SHINE experiment at CERN. All these constraints are used to calculate MC far detector prediction.

The far Super-Kamiokande (SK) detector is 50 kt water tank situated underground in Kamioka mine. Charged particles produced in neutrino interactions with the nuclei induce emission of Cherenkov light (provided they propagate with the velocity greater than velocity of light in water), which is recorded by PMTs installed on the walls of the tank. The light is emitted in cones, and their projections onto the walls are ring-shaped. Analysing topologies of the rings, we can distinguish e-like particles (electrons, gammas) from μ-like ones (muons, charged pions). An important background source in electron neutrino appearance analysis are NC π^0 production events, in which a π^0 decays into two photons, and these, in turn, generate two e-like rings; if an incident π^0 is energetic, the two rings can overlap, mimicking single e-like ring from electron, a signature of ν_e interaction. The same problem can be caused by one of the photons escaping from the detector.

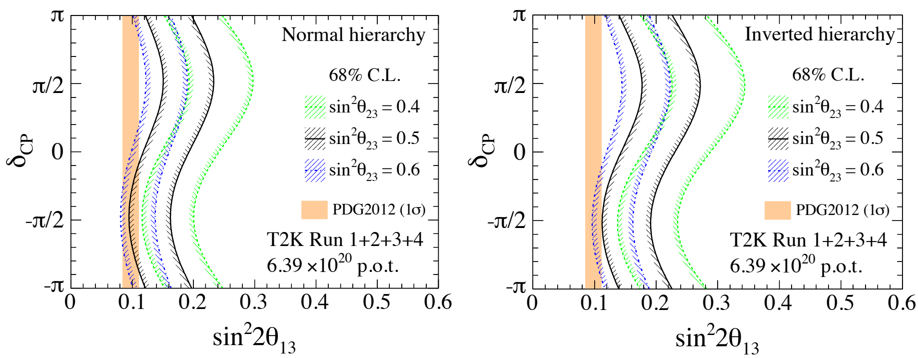

Fig. 3. Results of the T2K experiment. Fitted values of θ_{13} as a function of δ_{CP} for different hierarchies and values of θ_{23}. Grey/orange band represents PDG2012 reactor average value of $\sin^2(2\theta_{13}) = (0.098 \pm 0.013)$. Note: These are 1D contours for various value of δ_{CP}, not 2D contours. Pictures taken from [8].

In the ν_e appearance analysis, aiming at measuring θ_{13}, neutrino oscillation parameters were extracted in two ways: using reconstructed neutrino energy distribution and observed electron momentum and angle. The analysis that lead to results presented in 2013 [8] included new data collected last year as well as some upgrades to the 2012 analysis [7] — a new background rejection algorithm for SK was introduced and near detector CC inclusive measurement was improved by using new event categories. The T2K experiment observes 28 signal events; the expected background for this measurement is 4.64 ± 0.53 (assuming no oscillations). It is the first ever observation ($> 5\sigma$) of an explicit ν appearance channel [8]. The hypothesis of $\theta_{13} = 0$ can be excluded at the level of 7.5σ. Translating this into oscillation parameters, we get $\sin^2 2\theta_{13} = 0.150^{+0.039}_{-0.034}$ for normal hierarchy and $\sin^2 2\theta_{13} = 0.182^{+0.046}_{-0.040}$ for an inverted one (assuming $\delta = 0$, $\sin^2(2\theta_{23}) = 1.0$, $|\Delta m^2{}_{23}| = 2.4 \times 10^{-3}\mathrm{eV}^2$ and 68% C.L. error). The results are slightly larger than the ones obtained by the reactor experiments; one has to bear in mind, however, that the T2K measurement is δ, hierarchy and θ_{23} dependent, as can be seen in Fig. 3, presenting results for different values of these parameters, with the reactor result overlaid. A more precise T2K measurements of θ_{23} are expected soon as this parameter is measured in ν_μ disappearance.

The MINOS experiment is located in northern part of the U.S.A. [5]. Muon neutrinos from NuMi beam produced in Fermilab are detected in the far detector in the Soudan mine in Minnesota, 735 km from the beam source. Both far (3.8 kt of fiducial mass) and near (29 t of fiducial mass) detectors are magnetized tracking calorimeters. An interesting feature of MINOS is that the experiment have been using beams of neutrinos and antineutrinos, and both datasets were analysed to calculate the results. For ν_e appearance, the following values were obtained: $2\sin^2(2\theta_{13})\sin^2(\theta_{23}) = 0.051^{+0.038}_{-0.030}$ (for normal hierarchy, assuming $\delta = 0$ and $\theta_{23} < \pi/4$) and $2\sin^2(2\theta_{13})\sin^2(\theta_{23}) = 0.093^{+0.054}_{-0.049}$ (for inverted hierarchy, assuming $\delta = 0$ and $\theta_{23} < \pi/4$).

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