Neutrino mixing: results from accelertor experiments

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Recent progress from accelerator-based neutrino oscillation experiments is reported. ν_τ appearance from ν_μ was confirmed by Super-K and OPERA. Precise measurement of ν_μ disappearance by T2K shows value of θ_{23} still consistent with maximal mixing. ν_e appearance from ν_μ via θ_{13} was confirmed with 7.5σ significance by T2K. The non-zero θ_{13} discovered in 2012 implies the possibility to measure the CP-phase δ, mass hierarhcy and maximal or non maximal θ_{23}. T2K, NOvA and future projects will answer these questions.

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1. Introduction

The neutrino oscillation phenomenon tells us how the flavor eigen states and the mass eigen states mix in the lepton sector. The amount of the mixing is usually expressed in the form of a 3×3 unitary matrix:

$$
\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{bmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{bmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}
\tag{1.1}
$$

where the matrix is commonly parameterized as

$$
U = \begin{bmatrix} 1 & 0 & 0 \\ 0 & C_{23} & S_{23} \\ 0 & -S_{23} & C_{23} \end{bmatrix} \begin{bmatrix} C_{13} & 0 & S_{13}e^{-i\delta_{CP}} \\ 0 & 1 & 0 \\ -S_{13}e^{-i\delta_{CP}} & 0 & C_{13} \end{bmatrix} \begin{bmatrix} C_{12} & S_{12} & 0 \\ -S_{12} & C_{12} & 0 \\ 0 & 0 & 1 \end{bmatrix}
\tag{1.2}
$$

with C_{ij} (S_{ij}) representing $\cos\theta_{ij}$ ($\sin\theta_{ij}$). θ_{ij} is the mixing angle between the generations i and j. There is one irreducible phase, δ_{CP}, allowed and it would induce CP violation in the lepton sector. With the progresses made in recent years, now all the mixing angles are known[16]:

$$
\begin{aligned}
\theta_{12} &= 34° \pm 1° \\
\theta_{23} &= 40° + 5°/-2° \\
\theta_{13} &= \pm 0.6°.
\end{aligned}
$$

The remaining unknown parameter is the CP phase, δ_{CP}. We also don't know the sign of Δm_{32}^2, which determines the mass hierarchy among neutrinos. The current value of θ_{23} is close to and consistent with the maximal mixing ($45°$). The targets of the coming accelerator neutrino oscillation experiments are the measurement of δ_{CP} and possibly the discovery of CP violation in the lepton sector in case $\delta_{CP} \neq 0, \pi$, determination of the mass hierarchy and to prove how close θ_{23} is to full mixing.

Long baseline neutrino experiments use $O(1)$ GeV muon neutrino beams, detect them and identify the flavor at $O(100)$ km. The oscillation probability can be approximated by

$$
\begin{aligned}
P(\nu_\mu \rightarrow \nu_e) = \quad & 4C_{13}^2 S_{13}^2 S_{23}^2 \sin^2\Phi_{31}(1 + \tfrac{2a}{\Delta m_{31}^2}(1 - 2S_{13}^2)) \\
& + 8C_{13}^2 S_{12} S_{13} S_{23}(C_{12}C_{23}\cos\delta_{CP} - S_{12}S_{13}S_{23})\cos\Phi_{32}\sin\Phi_{31}\sin\Phi_{21} \\
& - 8C_{13}^2 C_{12}C_{23}S_{12}S_{13}S_{23}\sin\delta_{CP}\sin\Phi_{32}\sin\Phi_{31}\sin\Phi_{21} \\
& + 4S_{12}^2 C_{13}^2 (C_{12}^2 C_{23}^2 + S_{12}^2 S_{23}^2 S_{13}^2 - 2C_{12}C_{23}S_{12}S_{23}S_{13}\cos\delta_{CP})\sin^2\Phi_{21} \\
& - 8C_{13}^2 S_{13}^2 S_{23}^2 (1 - 2S_{13}^2)\tfrac{aL}{4E}\cos\Phi_{32}\sin\Phi_{31},
\end{aligned}
\tag{1.3}
$$

$$
P(\nu_\mu \rightarrow \nu_\mu) = 1 - (c_{13}^4 \sin^2 2\theta_{23} + s_{23}^2 \sin^2 2\theta_{13})\sin^2\Phi_{31},
\tag{1.4}
$$

where $\Phi_{ji} = \Delta m_{ji}^2 L/4E_\nu$. The terms which include $a \equiv 2\sqrt{2}G_F n_e E = 7.56 \times 10^{-5}[\text{eV}^2](\frac{\rho}{[g/cm^3]})(\frac{E}{[GeV]})$ give rise to the matter effect, and these terms change sign like δ_{CP} for anti-neutrinos. The electron neutrino feels a different potential than muon or tau neutrinos in matter because matter contains only electrons. This difference causes the matter effect. The matter effect is approximated to first

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order in $P(\nu_\mu \to \nu_e)$ given by Eq.1.3. It is neglected together with the Δm^2_{21} terms in $P(\nu_\mu \to \nu_\mu)$ given by Eq.1.4 because their contribution is very small. As can be seen in these equations, the $\nu_\mu \to \nu_e$ appearance measurement is particularly sensitive to $\sin^2 2\theta_{13}$ and δ_{CP}, while the $\nu_\mu \to \nu_\mu$ disappearance measurement is particularly sensitive to $\sin^2 2\theta_{23}$ and Δm^2_{32}.

2. ν_μ disappearance and $\nu_\mu \to \nu_\tau$ appearance

The most precise measurement on Δm^2_{32} so far was obtained by the MINOS experiments. The MINOS experiments measured the neutrinos produced by the FNAL NuMI accelerator complex and also neutrinos produced by cosmic ray interactions in the atmosphere. It started data taking in 2005 and finished in 2012. MINOS can distinguish ν_μ and $\bar{\nu}_\mu$ interactions by identifying the charge of the outgoing muons with a magnetized detector. Combining the data from the accelerator neutrino events and the atmospheric neutrino events, they obtained

$$|\Delta m^2_{atm}| = 2.39^{+0.09}_{-0.10} \times 10^{-3} \text{eV}^2$$
$$\sin^2 2\theta = 0.96^{+0.04}_{-0.04}$$

for ν_μ disappearance and

$$|\Delta \bar{m}^2_{atm}| = 2.48^{+0.22}_{-0.27} \times 10^{-3} \text{eV}^2$$
$$\sin^2 2\bar{\theta} = 0.97^{+0.03}_{-0.08}$$

for $\bar{\nu}_\mu$ disappearance[1]. Here Δm^2_{atm} is an admixture of the three-flavor parameters Δm^2_{31} and Δm^2_{32}, and it differs from Δm^2_{32} by less than 2%. θ is an effective two-flavor mixing angle and coincides with θ_{23} when $\theta_{13} = 0$. The $\Delta \bar{m}^2_{atm}$ and $\bar{\theta}$ are same as Δm^2_{atm} and θ, but are used to indicate values measured with $\bar{\nu}$. They find consistent values for neutrino and antineutrino oscillation parameters, as required from CPT symmetry.

In Japan, the Tokai-to-Kamioka(T2K) long baseline experiment has been running since 2010. Neutrinos produced at the J-PARC accelerator complex are, after traveling 295 km, detected by the Super-Kamiokande (Super-K) water Cherenkov detector. Super-K has a good capability to distinguish sub-GeV ν_μ and ν_e interactions by identifying an electron-like Cherenkov ring and a muon-like Cherenkov ring. They accumulated data with 6.63×10^{20} protons on target (POT) from the accelerator, which corresponds to 8.5% of the goal statistics. They released the result of ν_μ disappearance using data up to 3.01×10^{20} POT. As can be seen in Eq.1.4, the ν_μ disappearance probabilities are different depending on whether θ_{23} is smaller or larger than $45°$ if θ_{13} is not zero, even though the values of $\sin^2 2\theta_{23}$ are the same. Since θ_{13} has now now been precisely measured by reactor experiments[2][3][4], T2K showed the allowed region of $|\Delta m^2_{32}|$ vs. $\sin^2(2\theta_{23})$ for the cases of $\theta_{23} < 45°$ and of $\theta_{23} > 45°$ in Fig.1[5].

In the framework of the PMNS matrix, it is considered that atmospheric or accelerator-produced muon neutrinos mainly change to tau neutrinos. Since the threshold energy for the charged current (CC) interaction of the tau neutrino is relatively high (~ 3.5 GeV), we observe the 'disappearance' of muon neutrinos when the energy is not sufficient. The confirmation of the $\nu_\mu \to \nu_\tau$ oscillation is one of the important milestones for the understanding of the full picture of neutrino mixing. Super-K observed 3.8σ ν_τ appearance using enhanced τ-like samples from atmospheric data[7].
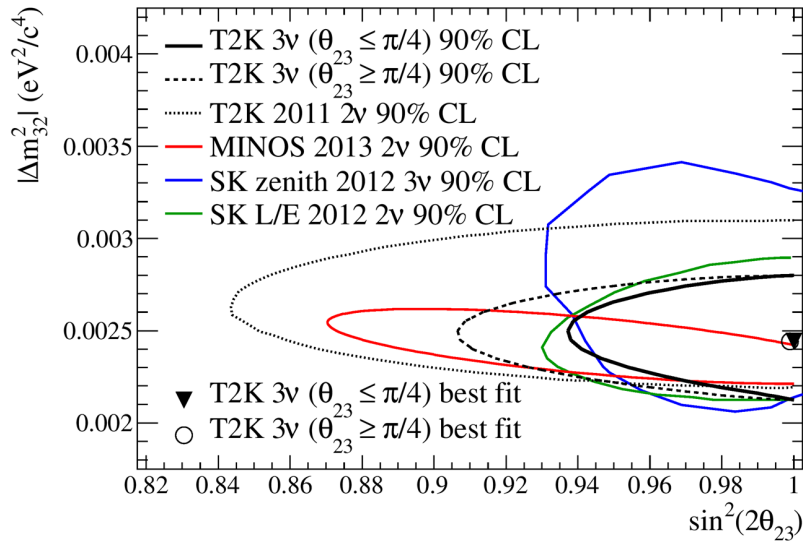
Figure 1: The allowed region of $|\Delta m_{32}^2|$ vs. $\sin^2 2\theta_{23}$ newly released by the T2K experiment. Those from MINOS[1] and Super-K[6] are overlaid.

Confirmation with a pure sample is also important. The OPERA experiment, using the beam from CERN SPS located 732 km away from the detector, identifies τ production event-by-event using nuclear emulsion. They analyzed about 60% of the data collected, and observed three ν_τ CC interaction candidate events. This corresponds to 3.2σ significance of ν_τ appearance [8]. Figure 2 shows the third candidate event of τ production by a ν_τ CC interaction, which was found in March, 2013.
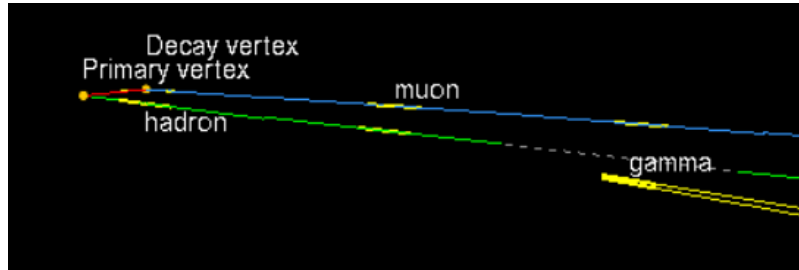

Figure 2: The third candidate event of τ production by a CC interaction of a ν_τ oscillated from a ν_μ observed by OPERA[8].

3. Anomalies at small L/E

The LSND (first report in 1995) and MiniBooNE experiments reported excesses of ν_e in ν_μ beams[9][10]. Event rates measured by many reactor experiments at short distances, when compared with a newly evaluated antineutrino flux, are indicating the disappearance of $\bar{\nu}_e$, together with the results from the gallium solar neutrino calibration experiments[11]. These are not explained within the standard three-neutrino-flavor framework. Some models explain these results by

neutrino oscillation to sterile neutrinos with a large mass squared difference ($\Delta m^2 > 10^{-2}$eV^2). The OPERA and ICARUS experiments have a good capability to identify ν_e interactions with nuclear emulsion or liquid Argon, and have measured it with the ν_μ beam from CNGS. They observed no excess of ν_e interactions and set upper limits on the effective mixing angle for the $\nu_\mu \to \nu_e$ oscillation, as shown in Fig.3([8][12]). The allowed region of $\Delta m^2 <$ sub eV^2 is excluded with the 90% C.L. However, the larger Δm^2 region still remains.
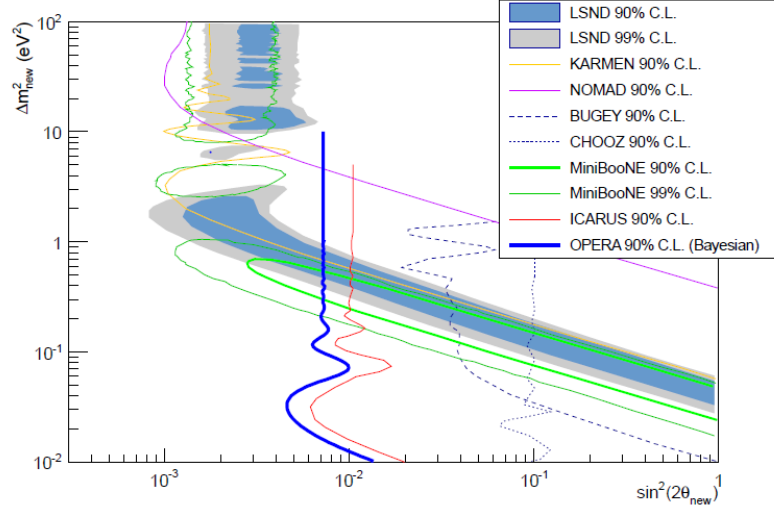
Figure 3: The upper limit on the mixing angle for $\nu_\mu \to \nu_e$ oscillation at various values of Δm^2 by OPERA(blue line) and ICARUS(red line). The allowed region by LSND and MiniBooNE are overlaid. Plot taken from [8]

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4. Progresses towards a precision measurement

Neutrino oscillation experiments have entered into the era of precision measurement. There are two major sources of uncertainty to be reduced for precision measurement: the accelerator neutrino flux and the neutrino-nucleus interaction with detector materials. Progress was reported by the NA61/SHINE experiment[13] and the MINERvA experiment[14] during the EPS HEP2013 conference.

NA61/SHINE is an experiment to measure the hadron production in hadron-nucleus and nucleus-nucleus collisions at the CERN SPS. It covers a wide range of the phase space of outgoing hadrons. Their measurements of the production cross sections for $\pi^\pm$, $K^\pm$, p and K^0_S for the 30 GeV p-Carbon interaction were used for the prediction of the T2K neutrino flux. Thanks to these measurements, T2K achieved a highly reliable prediction of the expected far detector observables: $10 \sim 20\%$ for the absolute flux and $\sim 2\%$ for the extrapolation of the flux from the near detector to the far detector. NA61/SHINE released a new result with higher statistics, which will reduce the T2K flux uncertainty further. They also measured the cross sections for the NuMI target at 120 GeV/c.

Although the elementary processes of the interactions of a neutrino with a lepton or a quark are well known, many complexities arise due to the dynamical features of multi-body systems such

as a nucleon and a nucleus. Lack of measurements causes a large uncertainty on the neutrino interaction with detector media ($10\% \sim 100\%$). Contradictory observations which current models cannot explain exist. MINERvA is a neutrino scattering experiment which uses the NuMI beamline at Fermilab. They reported the result of a charged current quasi-elastic scattering measurement[14]. This interaction is the signal mode of the T2K experiment and has the advantage that the neutrino energy can be reconstructed just by the outgoing lepton momentum and angle. However, it is affected by the nuclear system. The Q^2 distribution released by MINERvA favors a transverse enhancement, which suggests a contribution from the initial-state correlations of nucleons inside the nucleus.

5. ν_e appearance

In 2011, T2K reported an indication of ν_e appearance via non-zero θ_{13} with a 2.5σ significance, and MINOS did with a 1.7σ significance. Then, reactor experiments reported evidence of a non-zero θ_{13} with more than 5σ significance[2][3][4]. As can be seen in Eq.1.3, the ν_e appearance measurement would enable us to access the CP phase δ_{CP} either by comparing the $\nu_\mu \to \nu_e$ probability and the reactor $\bar{\nu}_e$ disappearance probability which is proportional to $\sin^2 2\theta_{13}$, by comparing the $\nu_\mu \to \nu_e$ and $\bar{\nu}_\mu \to \bar{\nu}_e$ probabilities, or more efficiently by comparing all of these.

MINOS placed constraints on the value of δ_{CP} by combining their measurement of ν_e appearance with the value of θ_{23} measured by ν_μ disappearance and the value of $\sin^2 2\theta_{13}$ measured by reactor experiments as shown in Fig.4[15]. The significance is still small, but it demonstrates that we are becoming sensitive to δ_{CP}.
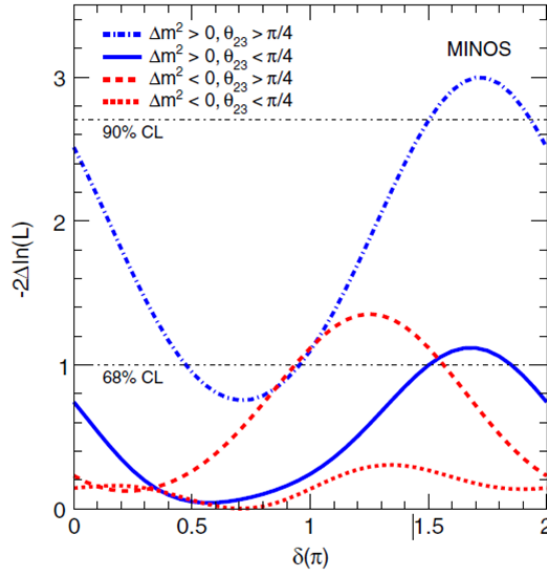
Figure 4: MINOS likelihood L, shown here as $-2\Delta \ln L$, as a function of δ_{CP}, assuming various values of the mass hierarchy and the octant of θ_{23}.

This year, T2K updated their measurement of ν_e appearance with improved background rejection and increased statistics[5]. The background contamination was reduced by about 30% with

a new Super-K reconstruction algorithm. The statistics were doubled: 3.01×10^{20} POT were analyzed in 2012 and 6.39×10^{20} POT in Apr 2013. The expected number of background events for the ν_e selection is 4.64 ± 0.51, while the observed number of events is 28. Figure 5 shows the reconstructed energy of the ν_e candidate events. With this observation, ν_e appearance was confirmed with 7.5σ significance. This is also the first time where the appearance phenomenon was confirmed with more than 5σ significance. They fit the final state electron (p, θ) distribution to get
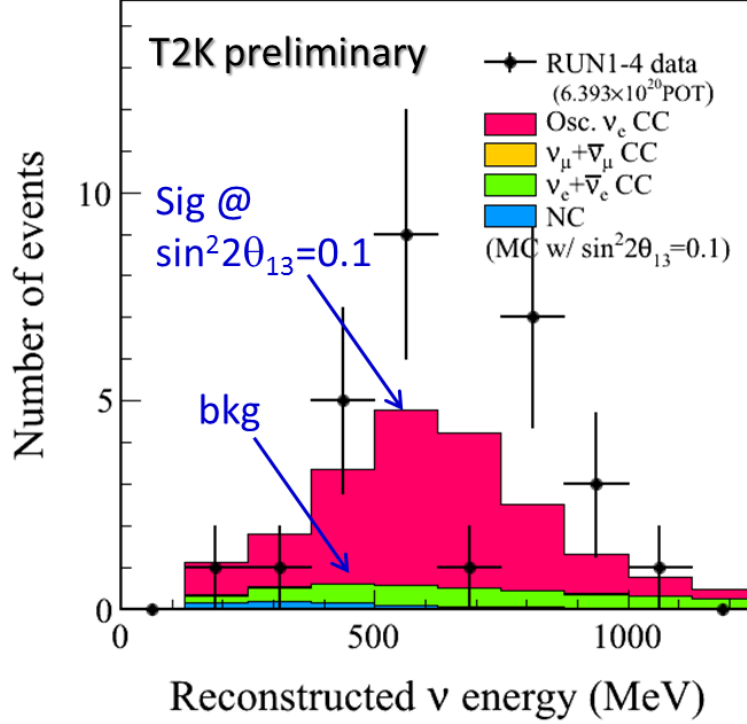
Figure 5: T2K Reconstructed neutrino energy spectrum of the ν_e candidate events[5]. Histograms show the contribution of different expected backgrounds together with the expected signal assuming $\sin^2 2\theta_{13} = 0.1, \delta_{CP} = 0$ and the normal mass hierarchy.

$\sin^2 2\theta_{13}$. The T2K best fit value of $\sin^2 2\theta_{13}$ when δ_{CP} is fixed to 0 and $\sin^2 2\theta_{23}$ to 1 is,

$$\sin^2 2\theta_{13} = 0.150^{+0.039}_{-0.034} \text{ for normal mass hierarchy}$$
$$\sin^2 2\theta_{13} = 0.182^{+0.046}_{-0.040} \text{ for inverted mass hierarchy},$$

while the reactor results are $\sin^2 2\theta_{13} = 0.098 \pm 0.013$[16]. The allowed regions of $\sin^2 2\theta_{13}$ are shown in Fig.6 for various values of δ_{CP} and $\sin^2 \theta_{23}$. They are very interesting and a result with more statistics is highly desired.

6. Future prospects

T2K has accumulated 8.5% of the target statistics so far and will try to do a 90% confidence level measurement of δ_{CP} and precise measurements of θ_{23} and Δm^2_{32}. In the US, the NOvA
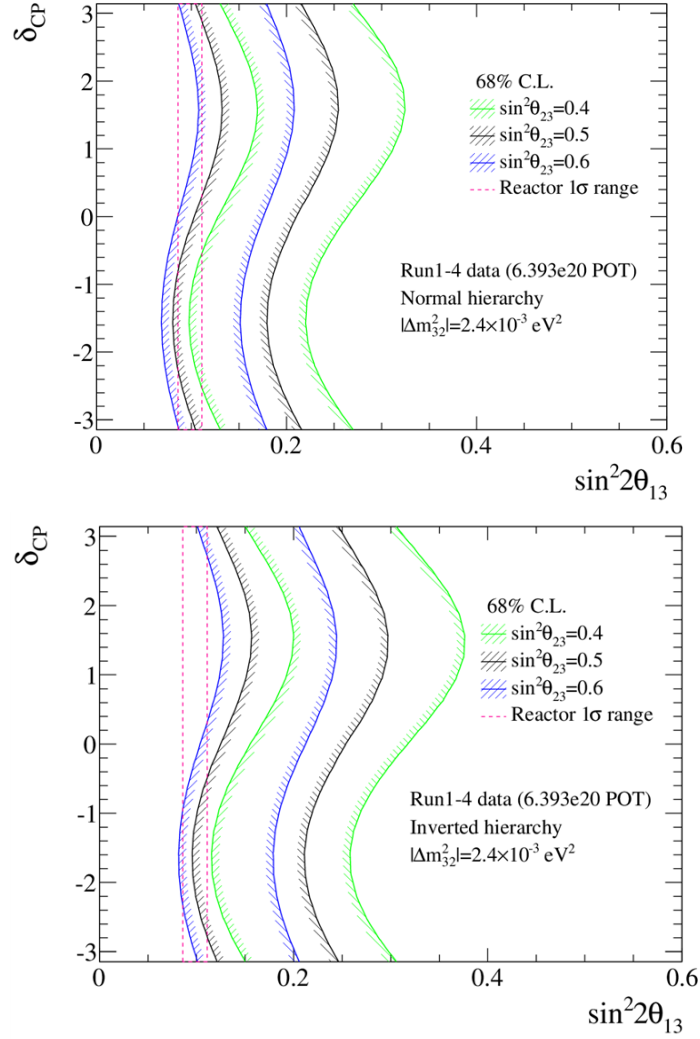
Figure 6: The allowed region of $\sin^2 2\theta_{13}$ for various values of δ_{CP} and $\sin^2 \theta_{23}$[5]. The top(bottom) panel shows the 68% CL region assuming the normal (inverted) mass hierarchy. The PDG reactor 1σ range is overlaid[16].

experiment was started beam commissioning. NOvA uses muon neutrinos from the NuMI beamline at Fermilab and detects them in Minnesota, 819 km away from the beamline. Their detector is made of liquid scintillator. About 40% of the detector was filled at the time of EPS HEP 2013[17], and filling is expected to be completed by April/May 2014. Since NOvA's baseline is 2.8 times longer than that of T2K, their neutrino energy at the oscillation peak and accordingly the size of the matter effect are larger by roughly same amount. Therefore, they have higher sensitivity to resolve the mass hierarchy. Furthermore, it is expected that sensitivities for CP violation and the mass hierarchy are significantly increased by combining the results from T2K and NOvA, two experiments at different baseline lengths. We may see the answer for the mass hierarchy and an indication of the CP violation at some point from these two experiments.

In the longer term, it is desirable to explore CP violation and the mass hierarchy with $> 3\sigma$

sensitivity. Many projects are proposed to achieve these goals[18]:

- LBNE, $L = 1,300$ km (Fermilab to SANFORD LAB, South Dakota), liquid Argon detector[19],

- Hyper-Kamiokande, $L = 295$ km (J-PARC to Kamioka), water Cherenkov detector[20]

- LAGUNA-LBNO, $L = 2,300$ km (CERN to Pyhasalmi), liquid Argon detector and/or liquid scintillator detector[18],

- EUROSB, $L = 540$ km, (European Spallation Source at Lund to Garpenberg), water Cherenkov detector (with many other options for far cite locations and detectors)[21].

7. Summary

Rapid progress was seen in the field of neutrino oscillation this year. ν_τ appearance from ν_μ was confirmed by Super-K and OPERA. Precise measurement of ν_μ disappearance by T2K shows a value of θ_{23} which is still consistent with maximal mixing. ν_e appearance from ν_μ via θ_{13} was confirmed with 7.5σ significance by T2K. The discovery of a non-zero θ_{13} in 2012 is not the end of the story, but is the start of a new quest: a search for CP δ, the mass hierarchy and maximal or non maximal θ_{23}. We may soon start seeing hints about CP δ from T2K and NOvA experiments, and future projects will firmly answer these questions.

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