IL NUOVO CIMENTO Vol. 37 C, N. 3 Maggio-Giugno 2014
DOI 10.1393/ncc/i2014-11766-6

Colloquia: Pontecorvo100

Long baseline accelerator neutrino experiments

K. Nishikawa
High Energy Accelerator Research Organization, KEK - Tsukuba, Ibaraki, Japan

Summary. — Neutrino oscillation has been observed and shown to be consistent with the idea that the oscillations are due to the co-existence of three mass and three flavor eigen-states. This is confirmed by the dependence on L/E and the observation of the explicit flavor changes associated with the oscillations in $\nu_\mu \to \nu_\tau$ and $\nu_\mu \to \nu_e$. The three mixing angles, which corresponds to the mixing of the three neutrino states, have been measured. They are large compared to those of quarks, especially the mixing of second and third generation is almost maximal. Reactor and accelerator data are consistent with three-neutrino framework at 10% level. Next generation long baseline neutrino experiments will clarify the mass hierarchy, relation of ν_μ, ν_τ and second, third mass states and may discover CP violation in neutrino oscillation. However, to investigate the structure of flavor physics further, it will be necessary to have critical tests of the three-neutrino framework itself and the origin of possible CP violation in lepton.

1. – Introduction

The long baseline experiments that we will discuss in this paper is to investigate physics at $\Delta m^2 \sim$ a few $\times 10^{-3}\text{eV}^2$ region. The advantages in carrying out a long baseline neutrino oscillation experiment using accelerator include the followings. First, the initial neutrino beam can be measured before the oscillation to occurs by placing a detector just after its production. Second, the distance L is fixed. The oscillation probability should have the functional form $\sin^2(1/E)$.

Presently, all accelerator-based experiments use the conventional method of producing neutrino beam. The neutrino is created through π and K productions and their decays. To achieve the highest possible neutrino intensity, horn-focused beams have been used. The neutrino beam is dominated by muon neutrino (ν_μ) with a few % electron neutrino (ν_e). Considering the charged current cross section, the ν_μ energy is better to be more than several hundred MeV, the baseline is required to be more than a few hundred kilo meters to investigate $\Delta m^2 \sim$ a few$\times 10^{-3}\text{eV}^2$ region.

K2K [1], MINOS [2], OPERA [3] and ICARUS [4] were the first generation experiments to investigate the muon neutrino(ν_μ) deficiency, reported by Kamiokande experiment [5]. They are exploratory experiments, designed to establish the existence of neutrino oscillation and try to be sensitive to wide range of Δm^2. The wide band spectrum of the horn-focused beam is well suited for these purposes. The weakness of this kind of beam is that the neutrino spectrum depends heavily on the π and K production kinematics in momentum and angle.

In K2K and MINOS, the main goal was to address the nature of ν_μ disappearance. The prediction of neutrino spectrum at far detector is the central issue. In neutrino experiments, the experimental observable is the event rate, which is the product of neutrino flux and cross section. Both quantities must be determined simultaneously to obtain spectrum. Using the measurements at two distances, the extraction of the spectrum can be done in principle. There are two problems. One is that the shape of spectrum at two different distances are not the same; i.e. it does not scale with distance due to the fact that the source of neutrino has finite volume for near detector but can be regarded as a point source for the far detector. The relation of flux at near and far location depends on parent π and K meson kinematical distributions. Once the knowledge of hadron production and/or in situ measurements of hadron distributions are available, neutrino at far detector can be calculated based on the measurements at near detector. In K2K, π and K production measurements by HARP experiment [6] were used. For T2K, measurements by NA49 experiment [7] at 30 GeV proton data were used. Other critical issue is that the detector must identify charged lepton to specify neutrino flavor and reconstruct neutrino energy. This makes the matching of the neutrino beam and detector characteristics to be one of the critical matter for the success of the experiment.

In K2K, the oscillation maximum will occur at a neutrino energy, E_ν, below GeV with $\Delta m^2 \sim 3\times10^{-3}\text{eV}^2$ and 250 km baseline. The E_ν can be reconstructed, using the charged current quasi-elastic interaction (CCQE), which has large fraction of events below 1 GeV. For both ν_μ and ν_e, the energy can be calculated by a formula:

$$E_{rec} = \frac{m_N E_l - m_l^2/2}{m_N - E_l + p_l \cos\theta_l}, \tag{1}$$

where m_N and m_l are the masses of the neutron and lepton (=e or μ), E_l, p_l and θ_l are the energy, momentum, and angle of the lepton relative to the neutrino beam, respectively. The actual extraction of neutrino spectrum was done by fitting the muon distributions in momentum and angle with a neutrino cross section model with quasi-elastic and inelastic reactions by using flux and cross section as variables. The lepton identification is based on the sharpness/fussiness of the Cherenkov ring. Figure 1 show a sample of single Cherenkov-ring events in K2K.

In MINOS, the oscillation maximum is at near 2 to 3 GeV due to the 730 km baseline. The E_ν is reconstructed as the sum of lepton energy and hadron energy.

$$E_{rec} = E_l + E_{had} \tag{2}$$

The lepton identification was based on the pattern of energy deposition in the segmented iron-scintillator sandwich detector.

In OPERA and ICARUS, the main goal was to confirm the conjecture that the ν_μ disappearance is due to the oscillation $\nu_\mu \to \nu_\tau$ by detecting τ decay in the detector. The spectrum measurements are less critical because the expected contamination of tau neutrino(ν_τ) is negligible in the initial beam, but the identification of tau neutrino is the critical issue. Considering the ν_τ charged current cross section and the available neutrino spectrum with 400 GeV proton at the CERN SPS, a wide band beam with 40

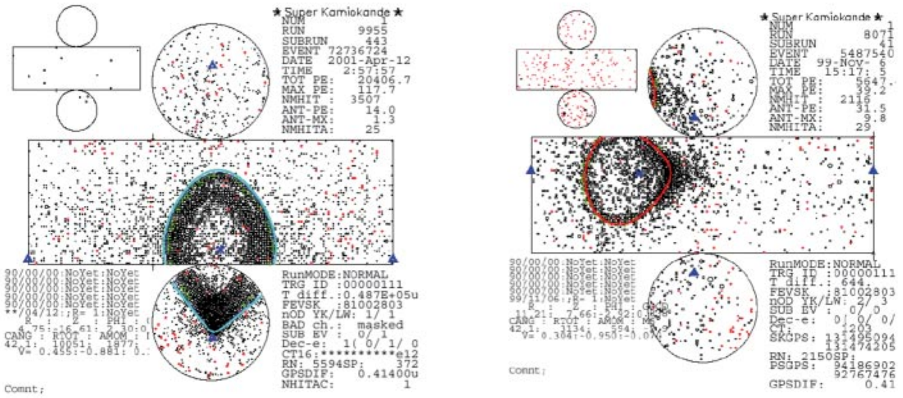

Fig. 1. – An event with single μ-like Cherenkov ring (left) and an event with electro-magnetic shower-like event (right) observed in K2K.

GeV peak neutrino energy was chosen. The ν_τ was identified by the production of τ and its sebsequent decay by looking for a short track/kink and topology of the events. This requires a detector with high granularity and track reconstruction capability in multi-track environments, like nuclear emulsion or liquid argon TPC.

T2K [8] is a second generation experiments, where Δm^2 is approximately known. The main goals are to measure ν_e in predominantly ν_μ beam and to improve the neutrino energy reconstruction for the improvements in ν_μ disappearance measurements. The experiments are optimized to suppress the backgrounds, such as π^0 neutral current events and inelastic events, by adopting off-axis beam to suppress high energy tail but keep the intensity at the necessary energy range. The off-axis beam was adopted for the first time in actual neutrino experiment by T2K, where the horn-focused secondary beam of π and K is directed to a direction with an angle relative to detector. The neutrino energy at an angle θ relative to π direction is

$$E_\nu(\pi\mu \text{ decay}) = \frac{0.49E_\pi}{1+\gamma^2\theta^2}\,, \tag{3}$$

where E_π, γ and θ are π energy, Lorentz factor of π and the angle of the direction of the secondary beam and the direction of detector, respectively. The spectrum at the angle θ has a Jacobian peak. In T2K, the angle was 2.5 degree, the resultant peak energy is 0.6 GeV. Possible high energy tail remains as a result of imperfect focusing of the secondary particles. The neutrino energy is well matched to the water Cherenkov detector in the neutrino energy reconstruction and in charged lepton identification.

The suppression of high energy tail in off-axis beam can be demonstrated in Figure 2, where the reconstructed ν_μ energy distribution for single muon events in the K2K wide band beam and in the T2K off-axis beam are shown.

2. – Results

2·1. ν_μ *disappearance at L(km)/E(GeV)* ≈ 500. – Oscillation behavior has been proved to be consistent as predicted in a framework of co-existence of mass and flavor eigenstates [9], i.e. not decay nor de-coherence etc. Figure 3 shows the oscillation behavior as

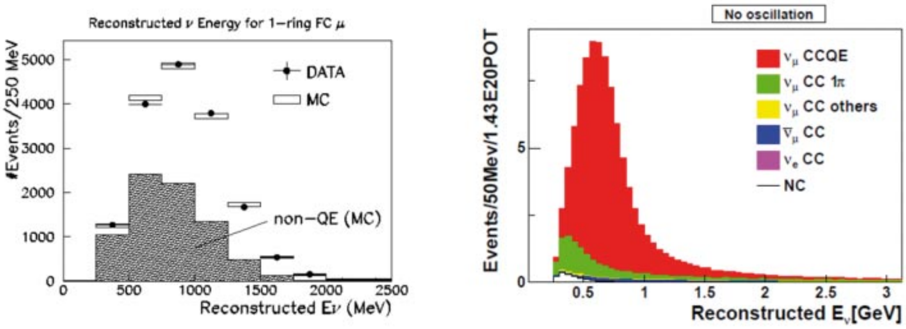

Fig. 2. – The reconstructed neutrino energy of the single muon events in K2K(left) and in T2K (right). The difference shows that the inelastic contamination are much smaller in T2K off-axis beam due to much smaller high energy tail.

a function of E_ν. MINOS results show clearly that the energy dependence and reappearance at low E (large L/E) are as predicted in a framework of co-existence of mass and flavor eigenstates. Also it was shown that the mixing angle and Δm^2 in neutrinos and in

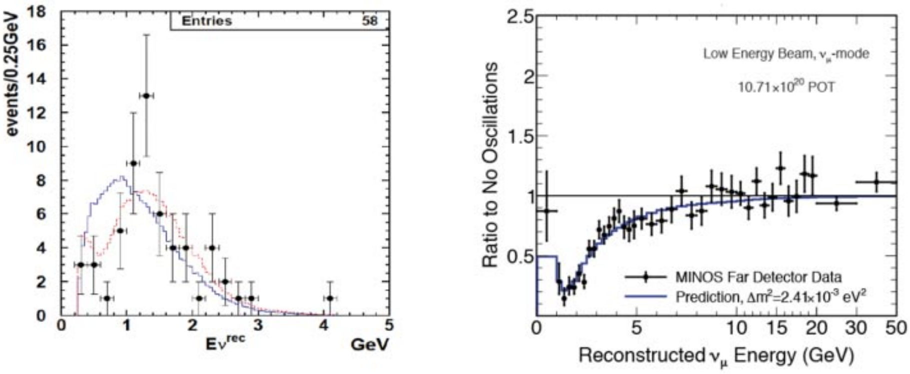

Fig. 3. – The oscillation behavior observed by K2K (left) and by MINOS (right). MINOS results show clearly reappearance at low E (large L/E) as predicted in a framework of co-existence of mass and flavor eigenstates.

anti-neutrinos oscillation are consistent each other within 1 σ by MINOS collaboration.

In T2K, due to the smallness of high energy tail in neutrino spectrum, inelastic neutrino events are expected to be small. Thus the fraction of mis-reconstruction of neutrino energy of single muon events by the equation (1) is small. Figure 4 demonstrates the cleanness of the neutrino energy reconstruction and the result of mixing angle.

OPERA collaboration found three ν_τ charged current events. The three events are identified as $\tau \to$ hadron, $\tau \to$3 hadrons, $\tau \to \mu$ decay events. The expected background for each event is 0.045, 0.090, and 0.065 events, respectively.

The ν_μ disappearance, which was observed in Kamiokande and Super-Kamiokande, is shown to be consistent with $\nu_\mu \to \nu_\tau$ oscillation. The mixing angle of second and third generation (θ_{23}) is almost maximal. However, the three-neutrino framework needs to be studied with higher precision.

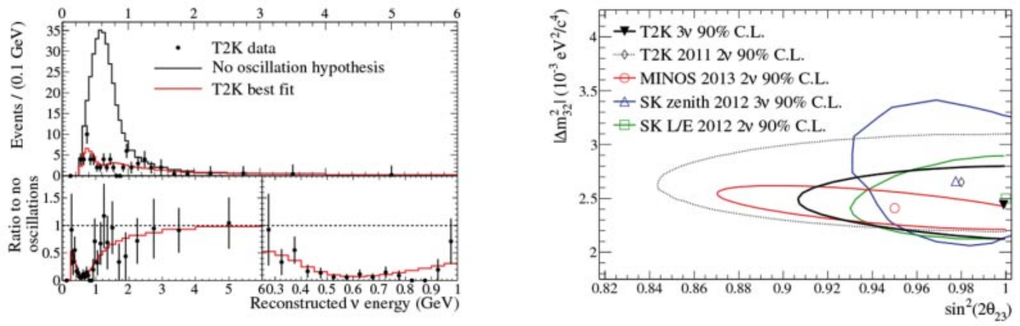

Fig. 4. – Left plot shows that the mis-calculation of neutrino energy due to contamination from inelastic events is small. This is due to the small high energy tail in T2K off-axis beam, Right plot shows a compilation of θ_{23} and Δm^2_{23} from MINOS, Super-Kamiokande and T2K results.

2·2. *$\nu_\mu \to \nu_e$ appearance at L(km)/E(GeV)* $\approx$ 500. – The rejection of neutral current π^0 is the critical issue in detecting ν_e appearance. Left plot in Figure 5 shows the rejection of π^0 by the ratio of π^0-likelihood and e-likelihood in the Super-Kamikande Monte Carlo study. The red line indicates the location of the π^0 rejection cut. Events in the upper right corner are rejected. The resultant reconstructed energy distribution is shown in right plot.

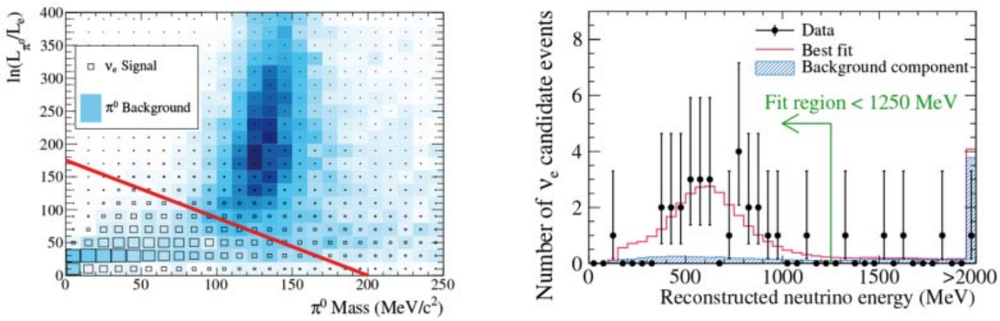

Fig. 5. – Left plot: the L_{π^0}/L_e vs m_{π^0} distribution is shown for both signal ν_e-CC events (boxes) and background events containing a π^0 (blue scale). The red line indicates the location of the π^0 rejection cut. Events in the upper right corner are rejected. Right plot: the E_{rec} distribution for ν_e candidate events compared with the MC prediction at the best fit of $\sin^2 2\theta_{13}$= 0.144 (normal hierarchy) by the alternative E_{rec} analysis.

T2K has made the first observation of electron neutrino appearance in a muon neutrino beam with a peak energy of 0.6 GeV and a baseline of 295 km. The significance for a non-zero θ_{13} is calculated to be 7.3σ, using the difference of log likelihood value between the best-fit θ_{13} value and θ_{13}=0. This means that there is an interference term of the oscillation amplitude with $\nu_2 - \nu_3$ and with $\nu_1 - \nu_2$ mass eigen-states in the oscillation $\nu_\mu \to \nu_e$. In the three-neutrino framework, performing the fit for all the values of δ_{CP}, the allowed 68% and 90% CL regions for $\sin^2 2\theta_{13}$ are obtained as shown in Figure 6.

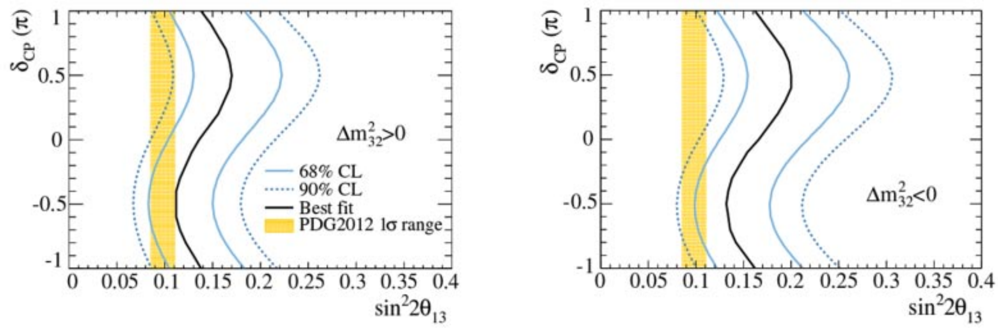

Fig. 6. – The allowed 68% and 90% CL regions for $\sin^2 2\theta_{13}$ as a function of δ_{CP}, assuming normal hierarchy (left) and inverted hierarchy (right). The shaded region shows the average θ_{13} value from the particle data group listing.

For $\delta_{CP} = 0$ and normal (inverted) hierarchy case, the best fit value with a 68% CL is $\sin^2 2\theta_{13} = 0.136^{+0.044}_{-0.033}(0.166^{+0.051}_{-0.042})$.

3. – Some thoughts on the future

The presently available measurements are the $\bar{\nu_e}$ disappearance of reactor neutrinos ($P(ee)$), ν_μ disappearance in atmospheric and accelerator neutrinos ($P(\mu\mu)$) and the ν_e appearance in ν_μ accelerator beam ($P(\mu e)$). They have unique relation in three-neutrino framework. To test the validity of three-neutrino framework, it is necessary to know whether $\theta_{23} \geq$ or $\leq \pi/4$, the sign of $(m_3^2 - m_1^2)$. These relationships may have important implications in flavor physics in general sense, i.e. the relationship of mass and flavor (or generation).

CP violation phase δ_{CP} is the last parameter to be measured in three-neutrino framework. Here, the measurement of δ_{CP} and the study of CP violation should be well distinguished. The real physics question is the origin of CP violation in leptons (if exist). It is not necessarily true that the δ_{CP} term dominate the CP violation effects as in quarks. The studies of CP violation in neutrinos may reveal the existence of new source of CP violation in neutrino oscillation and/or new interaction.

The discovery of non-zero θ_{13} gives us great opportunities to study mass, mixing and CP violation in lepton sector in depth, if right experimental ideas and right facilities are developed. The envisaged next generation long baseline experiments will be costly and need long term planning. It is critical to make right decision of which aspect to compromise, while keeping the maximum possible physics reach. The critical issues include accelerator power of multi MW, massive detector matched with neutrino energy, and proper way of predicting neutrino events at the far detector.

REFERENCES

[1] E. Aliu et.al. [K2K collab.], Phys. Rev. Lett. **94** (2005) 081802
[2] P. Adamson et.al. [MINOS collab,], Phys. Rev. Lett. **110** (2013) 251801
[3] N. Agafonava et.al. [OPERA collab.], arXiv:1308.2553[hep-ex]
[4] M. Antonello et.al. [ICARUS collab.], arXiv:1209.0122[hep-ex]
[5] Y. Fukuda et al. [Kamiokande collab.], Phys. Lett. **B335** (1994) 237
[6] M. G. Catanesi et al. [HARP collab.], Nucl. Phys. **B732** (2006) 1

[7] N. Abgrall et al. [NA61/SHINE Collab.], Phys. Rev. **C85** (2012) 035210
[8] K. Abe et.al. [T2K collab.], arXiv:1311.4750 [hep-ex]
[9] B. Pontecorvo, Sov.Phys. JETP **26** (1968) 984
Z. Maki, M. Nakagawa, and S. Sakata, Prog. Theor. Phys. **28** (1962) 870