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Long-Baseline Accelerator Neutrino Experiments

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We review the new results and recent progress in accelerator neutrino oscillation experiments. In 2010, a long-awaited tau signal of neutrino oscillation from a muon neutrino to a tau neutrino was detected in the OPERA experiment. A new-generation high-sensitive neutrino oscillation experiment, T2K, started physics data taking successfully. Finally, the neutrino oscillation parameters were measured more and more precisely in the MINOS experiment which also presented the first look at anti-neutrino oscillations. In addition to these promising progresses, there are a few anomalies not explained in the standard model with neutrino mass, which makes the studies of neutrinos more exciting.

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1. Introduction

The discovery of neutrino oscillation by Super-Kamiokande [1] gives a positive and concrete evidence of finite neutrino mass and makes it possible to study the neutrino mass and the mixing experimentally. After the discovery, the first long-baseline accelerator neutrino experiment, K2K, confirmed the discovery and measured the neutrino oscillations [2]. Now, the study of the neutrino mass and mixing becomes a very interesting and attractive subject in particle physics. Accelerator-based neutrino oscillation experiments play a key role to provide precise information on neutrinos.

In summer 2010, we have three big news about neutrinos. First, the OPERA experiment finds a long-awaited candidate event of ν_τ appearance in $\nu_\mu \to \nu_\tau$ oscillation [3]. Second, a new-generation high-sensitive neutrino experiment with an intense and high-quality neutrino beam, the T2K, launched out and collected the first physics data successfully [4]. T2K could provide the most precise measurements of neutrino oscillation parameters in $\nu_\mu \to \nu_\tau$ oscillation and the most sensitive search for $\nu_\mu \to \nu_e$ appearance to probe the non-measured mixing angle, θ_{13} [5]. Third, the MINOS experiment provides several new precision measurements of neutrino oscillations with both the neutrino and the anti-neutrino beams. In MINOS data, they may observe a different behavior between neutrinos and anti-neutrinos with limited statistic. So, it is an exciting time in 2010 for neutrino physics with these new results and progress. We enter a new era to reveal further mysteries of neutrinos, especially going on the road to the study of CP violation.

In this paper, we review the recent results and progress of the accelerator neutrino experiments. The physics targets of the accelerator neutrino experiments are

- Precise measurements of neutrino oscillations, especially for Δm^2_{23} and θ_{23}, in order to test the standard neutrino oscillation scenario with the Maki-Nakagawa-Sakata (MNS) neutrino mixing matrix.
- Discovery of the last oscillation channel $\nu_\mu \to \nu_e$ for θ_{13}.
- Study of CP violation in the neutrino sector, or any difference between neutrinos and anti-neutrinos.
- Determination of the mass ordering of neutrinos, the sign of Δm^2_{23}.

2. Observation of Tau Neutrinos

The discovery of the tau neutrino signal in the OPERA experiment was reported [7]. The high energy neutrino beam in OPERA with the mean energy of 17 GeV is produced at CERN in Switzerland and is shot toward the OPERA detector located in Gran Sasso National Laboratory in Italy 732 km away. The core technology of the OPERA detector is Emulsion Cloud Chamber (ECC) by which a kiloton-scale detector could get the micron-level resolution for the interaction vertex and the particle tracks to identify the tau neutrino interactions. [1]

The OPERA collaboration analyzed 35 % of 2008-2009 data corresponding to 1.89×10^{19} protons-on-target (POT). They detected a charged-current tau hadronic decay candidate event which

[1] The $c\tau$ of tau is only 87 μm.

occurred in August 22nd, 2009. The event has a kink of the track of 41 mrad and the decay length of 1335 μm which is a feature of the tau decay. Since the event has two photon candidates possibly coming from a π^0, the event topology is consistent with the decay of $\tau \to \rho \nu_\tau$ with $\rho \to \pi\pi^0$.

The expected number of signal events is $0.54 \pm 0.13(\mathrm{sys.})$ with the oscillation parameters of $\sin^2 2\theta_{23} = 1.0$ and $\Delta m^2_{23} = 2.5 \times 10^{-3}$ eV^2, while the expected number of background events is 0.045 ± 0.020 (0.018 ± 0.007) with the selection for all kinds (1 prong) of tau decay topologies. The statistical significance is calculated to be 2.01σ (2.36σ) for all kinds (1 prong) of tau decays. Although the OPERA detected the first tau candidate event, more signal events with more data are expected.

In addition to the OPERA $\nu_\mu \to \nu_\tau$ signal, Super-Kamiokande also found an indication of ν_τ appearance in atmospheric neutrinos with the statistical significance of 2.4σ [6].

3. T2K Starts

The Tokai-to-Kamioka (T2K) neutrino oscillation experiment [4, 5] is a new experiment with an intense and high quality neutrino beam. The T2K neutrino beam is produced by the Japan-Proton-Accelerator-Research Complex (J-PARC) which accelerates protons up to 30 GeV with the design beam power of 750 kW. T2K adopts a so-called "off-axis" neutrino beam technique by which the narrow-band energy beam is produced and the energy is tuned at the oscillation maximum. The beam has less high energy tails contributing to the background generation. The Super-Kamiokande (SK) detector is the far detector of T2K located 295 km away from the neutrino production target. SK is a 50 kt water Čerenkov detector with a very good performance for low energy neutrinos.

After a long construction period of J-PARC and T2K, the first neutrino beam was produced in April 23rd, 2009. After the commissioning period, the first neutrino events by the near detectors in J-PARC were detected in November 22nd, 2009. T2K started physics data taking in January 2010 and the first SK event was detected in February 24th, 2010. In the first running period from January to June 2010, T2K collected 3.35×10^{19} POT with a typical beam power of 50 kW. The neutrino beam focusing devices, three magnetic horns, were operated at 250 kA[2]. It was also tried to increase the beam power up to 100 kW for a short time, and the trial was successful.

The neutrino beam was measured by the near detectors located 280 m downstream from the target. The near detectors consist of the neutrino beam monitor, named INGRID, and the off-axis neutrino detector [8] which measures the neutrino beam going toward SK and measure the neutrino cross sections in the energy around 1 GeV. INGRID consists of 16 modular iron-scintillator sandwich detectors, and monitors the neutrino beam flux and the direction. The 14 INGRID modules are arranged as a cross of two identical groups along the horizontal and vertical axis and additional two modules are arranged at the off-diagonal position. The center of the INGRID crossing corresponds to the neutrino beam center defined as zero degree with respect to the direction of the primary proton beam line. The off-axis neutrino detector consists of two Fine-Grained detectors (FGD), three Time-Projection-Chambers (TPC), an Electromagnetic Calorimeter system (ECAL), Side-Muon-Range detectors (SMRD) and a π^0 detector (P0D). The detectors except for SMRD are

[2]The design current of horns is 320 kA, but it was operated with the lower current to minimize the risk of a break until the spare parts are available.

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located inside of the giant dipole magnet[3] operating at 0.2 T, and SMRD scintillator modules are installed in the gaps of the magnet yoke.

In Figure 1, the neutrino event rate measured by INGRID is shown as a function of the running time, which guarantees that the beam was stable for the entire running period. The neutrino beam profile is also shown in the figure, and the profile center corresponds to the neutrino beam direction. The neutrino beam direction is guaranteed to be as designed within 1 mrad. In the off-axis detector, many neutrino events were collected and we show some basic performances of the detectors. In Figure 2, the energy loss versus the momentum of the tracks measured by TPC is shown. In the positive tracks, we clearly identify the proton tracks around 800 MeV/c with high dE/dx, which are originated from the charged-current quasi-elastic interactions, $\nu_\mu + n \to \mu^- + p$. From the figure, the superior performance of TPC is demonstrated with a clear separation of the particle types. The analysis of the off-axis detector to measure the neutrino event rate and the energy spectrum is undergoing.

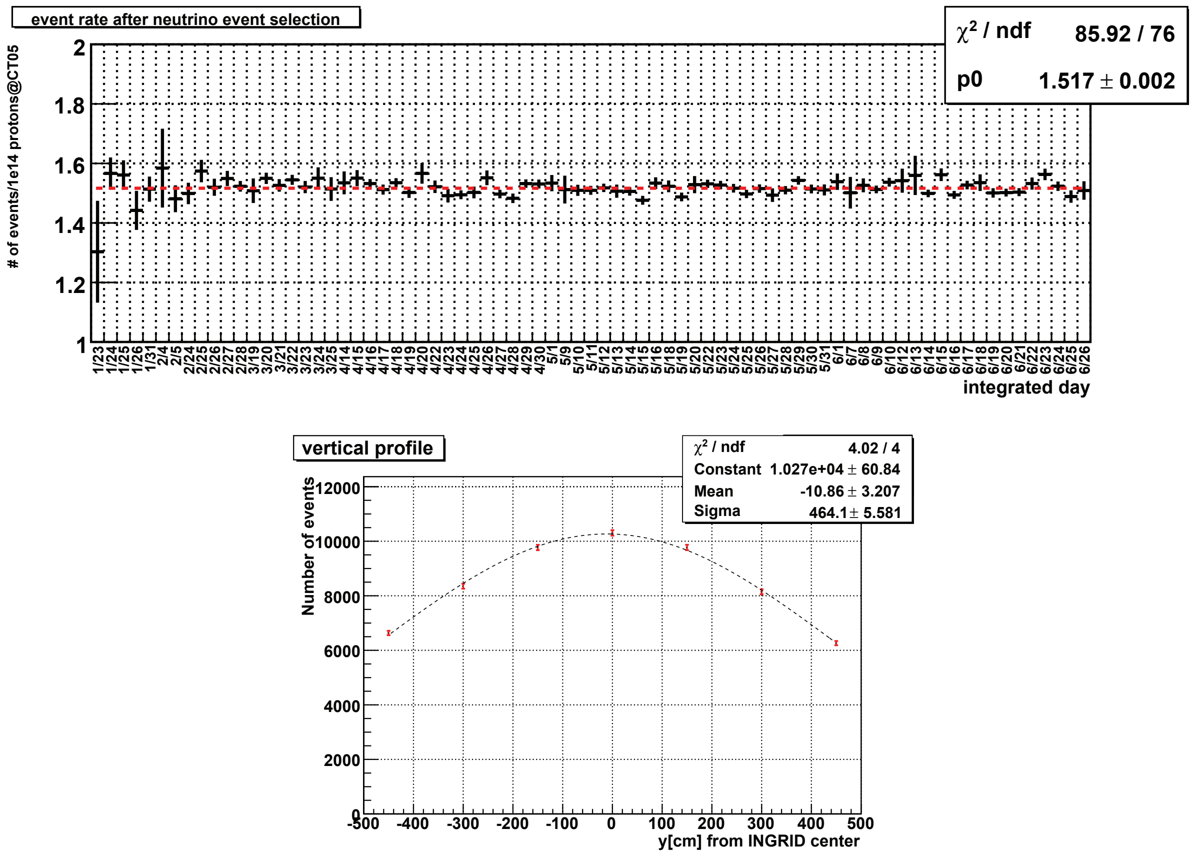

Figure 1: (Top) The neutrino event rate as a function of the running time at the near detector, INGRID. (Bottom) The vertical profile of the neutrino beam measured at INGRID.

The beam neutrino events in SK were selected by requiring the timing coincidence with the accelerator beam time. The accuracy of the timing coincidence is better than 100 nsec by using

[3] The magnet was used in the UA1 experiment and the NOMAD experiment at CERN.

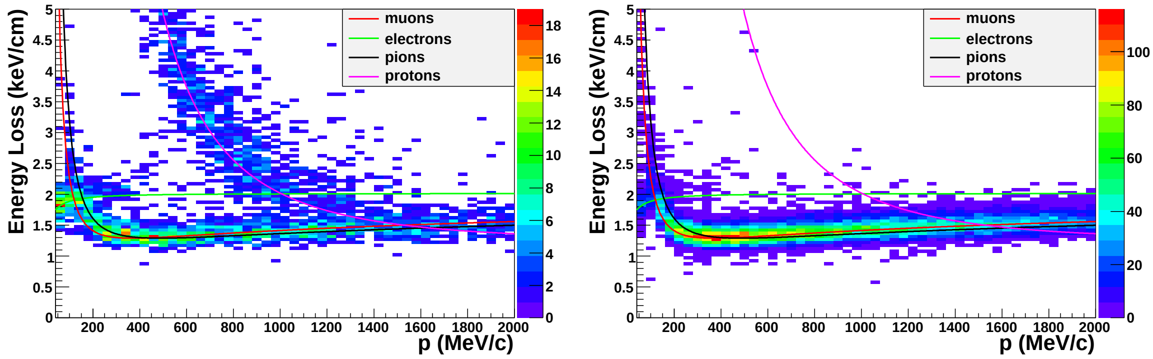

Figure 2: (Left) The momentum versus the energy loss of positive-charged tracks measured by TPC. (Right) The momentum versus the energy loss of negative-charged tracks measured by TPC.

GPS. The timing difference from the measurement to the expectation is shown in Figure 3. The beam timing structure, which has 6 bunches each separated by 581 nsec, is clearly seen. After requiring the fully-contained (FC) neutrino events without an activity in the outer detector, we observed 33 beam events while the non-beam background events are less than 10^{-3}. By requiring the events occurred in the 22.5 kton fiducial volume of SK, we select 23 events. Although T2K has no results on neutrino oscillations yet, the first results of neutrino oscillations with this 2010 data set is coming soon.

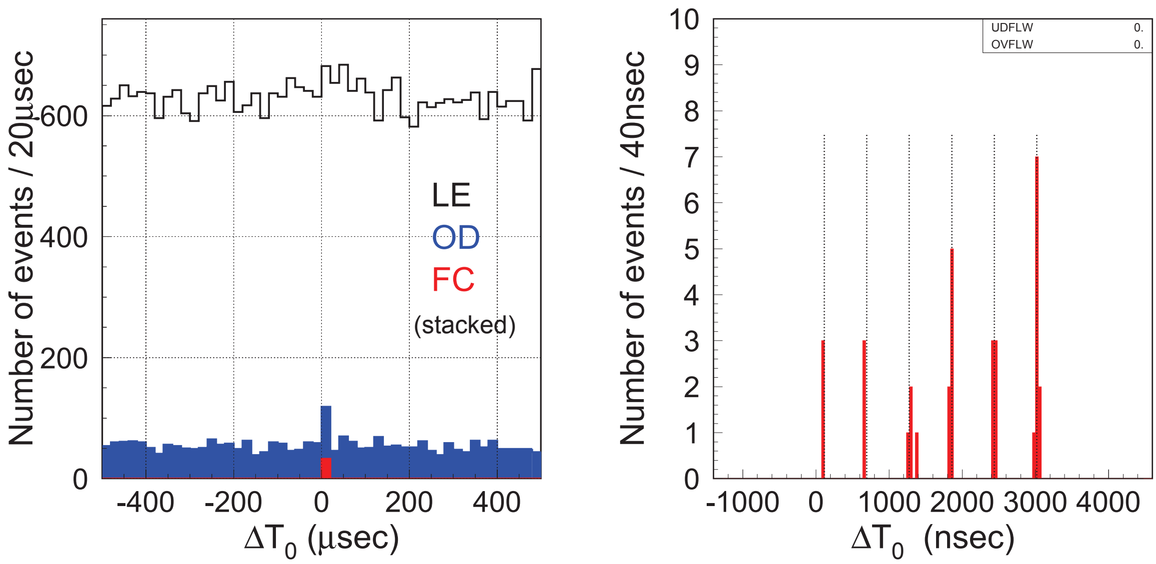

Figure 3: The timing distribution of the SK beam events relative to the expected arrival time. (Left) The wide time window of ±500 μsec. Three event categories are shown: LE (Low Energy events), OD (Outer Detector events) and FC (Fully Contained events). (Right) Zoomed-up time window from -1 μsec to 5 μsec.

The next T2K run will resume in fall 2010 and we plan to collect 10 times more data with the beam intensity beyond 100 kW before summer 2011. So, the results from T2K in the next few years are very exciting.

4. Precision Measurements of Neutrino Oscillations

Today, the most precise measurements of neutrino oscillations by accelerator experiments are provided by the MINOS experiment at Fermilab. The MINOS experiment started the data taking from 2005 and accumulated more than 1×10^{21} POT. The neutrino beam for MINOS, which is the most powerful neutrino beam today, was produced by Fermilab Main-Injector, and was delivered to the MINOS far detector 735 km away. In MINOS, both the neutrino and the anti-neutrino beams were produced by reversing the horn current. Several new results were presented at ICHEP2010 [9] and we introduce some of them below.

4.1 Precision measurements of neutrino oscillation parameters

The MINOS collaboration conducted the measurements of neutrino oscillation parameters by measuring the survival probability of muon neutrinos with neutrino mode data of 7.25×10^{20} POT. They observed 1986 events while 2451 events were expected without oscillations. They measured the oscillation parameters: $|\Delta m^2| = 2.35^{+0.11}_{-0.08} \times 10^{-3}$ eV^2 and $\sin^2 2\theta > 0.91$ at 90 % C.L.. It is one of the most precise measurements today. This measurement also excludes some exotic models of neutrino flavor change: the neutrino decoherence model is disfavored by more than 8 σ and the pure neutrino decay model is disfavored by more than 6 σ (7.8 σ if including the NC events).

4.2 Measurements of neutral current events

In order to confirm that the neutrinos do not disappear but oscillate, MINOS measured the rate of neutral current events. They observed 850 events with the expectation of 757 events. The measurement also gives a constraint on the oscillation to sterile neutrinos which could not be detected by the weak interactions. The upper limit on the probability of the neutrino oscillation to the sterile neutrinos is $f_s \equiv \frac{P(\nu_\mu \to \nu_s)}{1-P(\nu_\mu \to \nu_\mu)} < 0.40(0.22)$ at 90 % C.L. in the case of (no) electron neutrino appearance. The neutrino oscillation from ν_μ to active neutrinos, either ν_τ or ν_e, is firmly confirmed.

4.3 Search for electron neutrino appearance

Since the measurement of the last mixing angle θ_{13} is one of the most interesting topics in neutrino physics, MINOS searched for electron neutrino appearance. After the sophisticated electron neutrino selections, they observed 54 events with the expectation of $49.1 \pm 7.0 \pm 2.7$ background events with 7.01×10^{20} POT. Since the observed events were consistent with the background, they set upper limits on $\sin^2 2\theta_{13} < 0.12$ at 90 % C.L. for the normal hierarchy case ($\Delta m^2 > 0$) and $\sin^2 2\theta_{13} < 0.20$ at 90 % C.L. for the inverted hierarchy case ($\Delta m^2 < 0$) by assuming the other parameters to be $\delta_{CP} = 0$, $\theta_{23} = \pi/4$ and $\Delta m^2_{23} = 2.43 \times 10^{-3}$ eV^2. This is one of the best limits on θ_{13} today.

4.4 Measurement of anti-neutrino oscillation

In order to test the CPT invariance in neutrino oscillations, the anti-neutrino oscillation was measured by MINOS with the anti-neutrino beam data of 1.71×10^{20} POT. The anti-neutrino beam for MINOS consists of 39.9 % of anti-muon neutrinos, 58.1 % of muon neutrinos and 2 % of anti-electron and electron neutrinos, while the neutrino beam consists of 91.7 % of muon neutrinos, 7 % of anti-muon neutrinos and 1.3 % of electron and anti-electron neutrinos. They observed the disappearance of anti-muon neutrinos and measured the survival probability as a function of the reconstructed neutrino energy. They found that the best fitted values of the parameters were $|\Delta\overline{m}^2| = 3.36 \times 10^{-3}$ eV^2 and $\sin^2 2\overline{\theta}_{23} = 0.86$. Although they found that the best fitted values of the anti-neutrino oscillation were not same as those of the neutrino oscillation, the current measurement was limited by statistics. MINOS plans to collect more anti-neutrino data to get a conclusive result.

For the CPT test, the SK collaboration also looked for the difference of neutrino oscillation parameters between neutrinos and anti-neutrinos in the atmospheric neutrino data [10]. Although SK could not separate the neutrino interaction from the anti-neutrino one on an event-by-event basis, SK could statistically see the difference of kinematic distributions between neutrinos and anti-neutrinos. They measured the oscillation parameters in atmospheric neutrinos to be $|\Delta\overline{m}^2| = 2.0 \times 10^{-3}$ eV^2 and $\sin^2 2\overline{\theta}_{23} = 1.0$ for anti-neutrinos and $|\Delta m^2| = 2.2 \times 10^{-3}$ eV^2 and $\sin^2 2\theta_{23} = 1.0$ for neutrinos. They find no evidence of CPT violation in neutrino oscillations.

5. Anomaly

Among many recent results from the accelerator neutrino experiments, there are a few interesting anomalies which could not be explained in the standard model with a standard neutrino oscillation scenario. One of them is the anti-neutrino oscillation measurements by MINOS reported in Section 4.4 although the statistical significance is not high. Another one is the so-called "low energy excess" observed by the MiniBooNE experiment [11] in short baseline neutrino oscillation search for the large Δm^2 region. In MiniBooNE, they do not confirm the LSND anti-neutrino oscillation in the neutrino beam at 90 % C.L., but they observe the unexpected excess of electron-like events in the lower energy region with 3 σ significance. They do not find the source of the excess and the excess remains as an anomaly. No other experiment observes the excess nor the similar phenomena. MiniBooNE also searched for the phenomena of the LSND anti-neutrino oscillation in the anti-neutrino beam, and they find the signal of oscillation. The signal is consistent with the LSND result at 99.4 % C.L. relative to null. Since no other experiment looks for the LSND anomaly, the MiniBooNE proposes to collect more anti-neutrino data to get more conclusive results.

6. Future Prospects

Today, we live in the very exciting stage where we wait for the new discovery just around the corner. Twelve years after the discovery of the neutrino oscillation and the neutrino mass, we get precise information on neutrino oscillation parameters in our hand: the mixing angle and the mass square difference. Now, we are eager to find the last of the mixing parameters θ_{13}, the ordering of the neutrino mass and the CP violation effect. Especially, the CP violation is one of the most fascinating phenomena in science, which we discovered so far. Because no anti-matter exists in our universe, nature tells us that CP violation is the key to build our universe. So far, we only know one source of CP violation in the Kobayashi-Maskawa model which could not explain the asymmetry between matter and anti-matter in our universe. So, we know that there are definitely more sources of CP violation, but we do not find them yet. Since the phenomena of neutrino oscillation could provide the testing ground of CP violation in neutrino sector, the study of CP violation in neutrinos may give a hint on the asymmetry between matter and anti-matter. For these purposes, there are several new experiments discussed, designed and proposed all over the world. Soon, we will enter the new era to study CP violation in neutrinos.

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