T2K Experiment :

T2K (Tokai-to-Kamioka) experiment detected indication of electron neutrino appearance in muon neutrino beam after 295km travel from J-PARC to Super-Kamiokande

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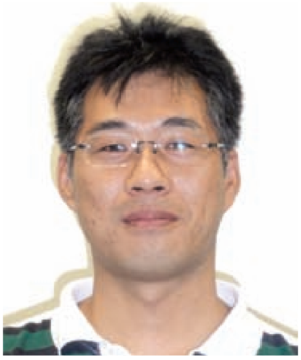

The neutrino is one of the elementary particles whose properties are among the most unknown. Even the mass, one of the fundamental properties of a particle, is yet unknown. Theoretically it has long been assumed to be massless, but experiments conducted in 1998 at Super-Kamiokande (SK) discovered evidence of neutrino oscillation which proved that neutrinos are massive [1]. This was the first evidence of phenomena which the present Standard Model (SM) of elementary particles has not supposed. Since then, neutrinos have been attracting great attention from particle physicists, who expect that neutrinos could provide a breakthrough in exploring physics beyond the SM.

Neutrino oscillation is a phenomenon whereby the type (flavor) of neutrino changes during flight in an oscillatory manner. There are three types of neutrinos, ν_e, ν_μ and ν_τ. The oscillation can occur when the three neutrinos are mixtures of three states ν_1, ν_2, ν_3 with definite masses (m_1, m_2, m_3). The mixings are parameterized by three mixing angles θ_{12}, θ_{13} and θ_{23}, and CP violating phase δ_{CP}. The amplitude of the flavor change is determined by those parameters and the frequency (or wave length) of the oscillation is determined by the differences of the mass eigenvalues ($\Delta m_{ij}^2 \equiv m_i^2 - m_j^2$). The existence of oscillation means that the mass eigenvalues are different from each other, i.e., at least one neutrino is massive.

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The discovery of SK in 1998 is a disappearance of ν_μ, which is a decrease of ν_μ due to the oscillation to the other types of neutrinos in atmospheric neutrino observation. After that, the K2K (KEK to Super-Kamiokande long-baseline neutrino oscillation) experiment confirmed it using an accelerator-produced ν_μ beam [2]. Additionally, oscillation from ν_e to the other types was discovered in neutrinos from the Sun and nuclear reactors [3-5]. In the experiments, the mixing angles θ_{12}, and θ_{23} were measured and found to be relatively large, while θ_{13} has only an upper bound [6] and δ_{CP} is left completely unknown. The determination of θ_{13} has been the most important and urgent target for the last 10 years in the neutrino community because the feasibility to judge whether CP symmetry is violated or not in a neutrino (i.e., whether δ_{CP} is zero or not) solely depends on the size of θ_{13}.

The T2K (Tokai-to-Kamioka) experiment is designed and optimized for the measurement of last unknown angle θ_{13}. An intense ν_μ beam is produced at the Japan Proton Accelerator Research Complex (J-PARC)[7] in Tokai village and is detected by SK, which is 295 kilometers from J-PARC (Fig.1). The method to probe θ_{13} is to look for and measure the oscillation from ν_μ to ν_e (ν_e appearance) whose probability is proportional to $\sin^2 2\theta_{13}$. Another important goal of T2K is to determine already known parameters much more precisely by measuring ν_μ disappearance.

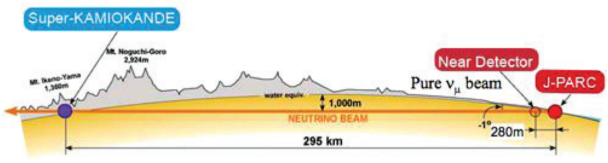

Fig. 1: Overview of T2K experiment

The muon neutrino beam is generated from decays of pions produced by hitting a graphite target with the 30GeV pulsed proton beam from the Main Ring in J-PARC once per ~3sec. The pions from the target are focused by a series of three electromagnets called "horns" operated at 250kA pulsed current in order to increase the neutrino flux at SK, and then decay to ν_μ (and muons) during flight in subsequent 96m long volume called "decay volume". After 295 kilometers of travel, the ν_μ beam passes through the SK detector, which is 39 meters in diameter and 42 meters high, making it the world's largest water Cherenkov detector as it is filled with 50 kt pure water.

T2K started continuous beam operation and physics data taking in Jan. 2010. The beam intensity had gradually increased and reached 145kW ($\sim 0.9 \times 10^{14}$ protons/pulse) until just before March 11, 2011. On that date a large earthquake hit east Japan and forced data taking to stop. During the whole period of data taking from Jan. 2010 to Mar.11, 2011, the total number of protons which hit the target is summed up to 1.43×10^{20}.

On June 15th, 2011, we released the first results of the ν_e appearance search using data which was taken before the earthquake [8].

In the analysis, first, the interactions of neutrinos coming from J-PARC are identified by the timing information measured using GPS with <100ns precision. The expected beam arrival time at SK is calculated by adding the time when proton beam hit the target and the time of flight from J-PARC to SK (~1ms). By selecting events in SK around the expected arrival time with a 12us time window, we can clearly select neutrino interactions by J-PARC neutrinos with negligible background. We have detected 88 neutrino interactions in SK fiducial volume of 22.5kt.

In order to identify ν_e interactions among 88 events, Cherenkov photon distribution is used. The type of neutrino can be distinguished by the type of lepton which emerges from the neutrino interaction; an electron from ν_e and a muon from ν_μ. An electron produces an electromagnetic shower in water and many electrons and positrons are produced which generate Cherenkov photons. As a result, a Cherenkov ring projected on the inner wall becomes fuzzy with many scattered lights. On the other hand, because a muon does not make an electromagnetic shower and goes relatively straight, a Cherenkov ring becomes clear with a sharp outer edge. Particle identification (PID) likelihood is defined by quantifying such differences and provides good electron identification with ~1% misidentification. After requiring only one electron like ring exists with additional criteria to further reduce possible background contamination, we finally find 6 ν_e candidate events. The expected number of background events with the assumption of $\theta_{13}=0$ is estimated to be 1.5 ± 0.3 using measured beam properties and simulations. The reconstructed neutrino energy distribution of the final sample is shown in Fig.3 (left).

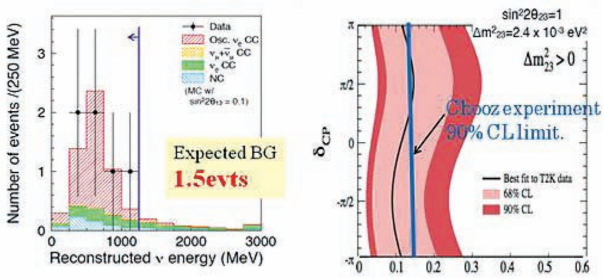

Fig. 3: (Left) Neutrino energy spectrum. Dots are data, histograms are expected distributions of signal (red hatched) and backgrounds (others). (Right) Allowed regions

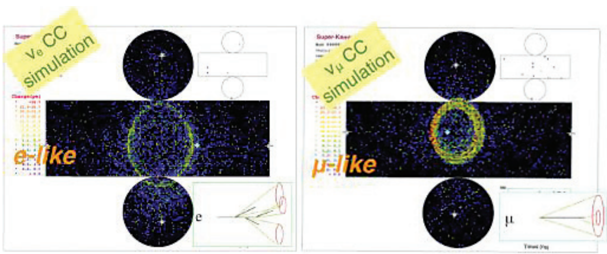

Fig. 2: Typical Cherenkov light distributions of electron and muon (simulation)

We evaluated the probability that $\theta_{13}=0$ and the observed number of event, 6, is explained by just a statistical fluctuation of background contamination and is found to be 0.7%. The corresponding significance of the excess over the background is 2.5σ level. Then assuming this excess is due to non-zero θ_{13}, we obtained allowed region of θ_{13} as shown in Fig.3 (Right). The allowed region depends on the unknown δ_{CP} and is $0.03 < \sin^2\theta_{13} < 0.28$ (90%CL) and best fit value is $\sin^2\theta_{13} = 0.11$[1)] at $\delta_{CP} = 0$.

This observation is the long-awaited first direct indication of non-zero θ_{13}. The most probable value of $\theta_{13}=0.11$ is large enough to make the detection of CP

1) These are for the case $\Delta m^2_{23} > 0$. In case for $\Delta m^2_{23} < 0$, slightly shifted values are obtained

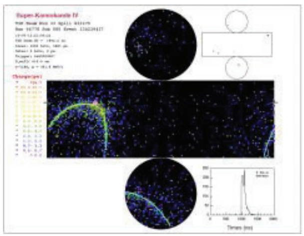

Fig. 4: Event display(Cherenkov light distribusion) for one of the signal candidate events

violation realistic with straight forward extension of the present scheme with ν_μ beam from horn-focused pions, although further upgrades of the accelerator and detector will become necessary. Since the size of θ_{13} decides the future direction, the most important and urgent goal is to conclude finite θ_{13} and determine it more precisely as soon as possible.

The T2K experiment and J-PARC accelerators were forced to stop operation due to the earthquake. Recovery works are being made and we plan to restart accelerator operation in Dec. 2011. T2K will restart data taking as soon as possible after the accelerator and the beamline have finished re-commissioning.

References

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