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E362 : Results from K2K experiment and T2K : a New Generation Neutrino Oscillation Experiment

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I. INTRODUCTION

Bruno Pontecorvo(1959) and Melvin Schwartz(1960) independently realized the possibility to produce an intense neutrino beam from the decay of pions, that are produced abundantly by strong interaction in the collision of a proton beam. In the first step, a proton beam hits a nuclear target and generates secondary pions: $p + nucleus \rightarrow \pi^+ + anything$. In the second step, the pions decay according to $\pi^+ \rightarrow \mu^+ + muon\ neutrino(\nu_\mu)$. The neutrino energy is given by:

$$E_\nu = \frac{m_\pi^2 - m_\mu^2}{m_\pi^2} \times \frac{E_\pi}{1 + \theta_\pi^2 \times \gamma_\pi^2}$$

where $m_\pi, m_\mu, E_\pi, \theta_\pi$, and γ_π are pion mass, muon mass, pion energy, angle relative to the beam axis, and gamma factor of the π, respectively. All of the particles, except neutrinos, are absorbed in a thick shield. Since the decay $\pi \rightarrow e + neutrino$ is suppressed, neutrinos are predominantly ν_μ. The electron neutrinos (ν_e) are produced in the pion decay chain: $\pi \rightarrow \mu + \nu_\mu$, $\mu \rightarrow e + \nu_\mu + \nu_e$ and K_{e3} decays: $K \rightarrow \pi + e + \nu_e$. Typical fraction of ν_e is at a few % level of total flux, which is due to the longer lifetime of μ and the small braching ratios of K_{e3} in kaon decays.

On the average, more than one pion are produced per interaction in multi-GeV proton interaction with nucleus. The dominant part of produced pions have a few 100 MeV transverse momentum and a wide range of momentum. A focusing device must have a similar transverse momentum kick. Because the decay process of pions and kaons is involved, the core of a GeV neutrino beam has a divergence of an order of milli-radian. Because of the unavoidable neutrino beam divergence and a long distance needed, a long baseline experiment needs the highest possible neutrino intensity.

Several types of the beam have been used in accelerator-based neutrino experiments, such as "Sign Selected Beam" (sign and energy band selected by dipoles, focusing by quadrupoles magnets), "Narrow Band Beam" (pion momentum is selected and focused by quadrupole magnets), and "Beam dump beams" (injecting protons in a large absorber and stop all the produced particles in the absorber, thus suppressing π, K decays and enhance prompt decay products, like ν_τ).

The highest possible neutrino intensity can be obtained by collecting pions, regardless of their energies, into the direction of the detector by a magnet with the shortest focal length (wide band beam). Presently, a horn magnet, which was invented by S. van der Meer in 1961 [1], can attain the shortest possible focal length by focusing in both x- and y-direction simultaneously. It consists of two coaxial cylindrical conductors, which are connected electrically in series. By applying a high current pulse on the conductors, a toroidal field is produced between two conductors. Figure 1 shows an example of the horn used in K2K.

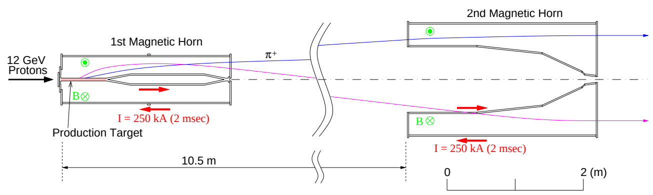

FIG. 1: Schematic view of the two horn magnets, used in K2K. An electric current of 250 kA was supplied to the both horns, creating a toroidal magnetic field inside the horns. The second horn is located downstream of the first horn to increase the acceptance of the horn system.

In accelerator neutrino experiments, the energy and distance can be controlled and the measurements can be done at two locations. This has one advantage, since all observed quantities in neutrino experiments are products of flux and cross section. Measurements at the two locations eliminate most of ambiguities due to neutrino cross sections, but generally the ratio of the neutrino flux at far to the one at near (F/N ratio) depends on neutrino energy.

For neutrinos from a point-like and isotropic source, the flux scales with distance as $1/L^2$ and the F/N ratio is constant. In a wide band neutrino beam, the source is extended in the decay volume and its distribution depends on the meson energy distribution (decay length). The extended nature of the source makes F/N ratio to decrease with energy, whereas the Lorentz boost in meson decay makes F/N ratio to increase with energy. The net effect is that the F/N ratio has a characteristic "dip" in energy, which could fake oscillations, if the pion production is not modeled properly.

II. RESULTS FROM K2K EXPERIMENT

The KEK to Kamioka (K2K) neutrino oscillation experiment was proposed in 1996 to establish the neutrino oscillation, which was hinted in atmospheric neutrino observations by the Kamiokande collaboration. The reduction of neutrino events and the change of the spectrum were looked for. The experiment used the 12 GeV proton beam from a synchrotron at KEK and the Super-Kamiokande water Cherenkov detector (SK) [2]. The baseline is 250 km and the maximum oscillation is expected to occur at less than 1 GeV for $\Delta m^2 \sim 3 \times 10^{-3}\mathrm{eV}^2$. Data had been accumulated from June 1999 to July 2001 and January 2003 to November 2004. The total accumulated number of protons on target was 92.2×10^{18}. The final results were published in 2006 [3].

The K2K beam line consists of a two interaction length Aluminum target, a double horn system to focus secondary positive pions, a 200 m decay volume, followed by a muon monitor. Protons are extracted by fast kicker magnets with about 5.5×10^{12} protons/pulse (ppp), every 2.2 s, with 1.2 μs spill duration. Figure 2 shows the expected neutrino energy spectrum at near detector and SK by a beam Monte Carlo. The results of pion production

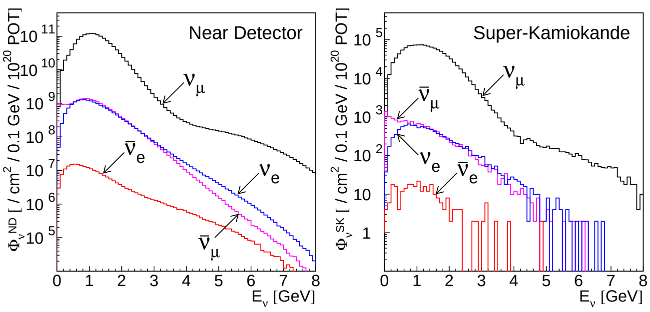

FIG. 2: The predicted neutrino energy spectrum for each type of neutrinos at ND(left) and SK(right). The spectra at two locations are expected to be different. The neutrino source is a finite length line source from the point of view of ND, whereas SK see the source as a point one. The relation of spectra at ND and SK is determined once the pion distribution in momentum and angle is known.

off Aluminum target at 12 GeV protons from the HARP collaboration [4] was used as the pion production model, which is consistent with old experimental data [5]. The pion production was also checked by a gas Cherenkov detector, placed after the horn system(PIMON) [3]. The two dimensional momentum and angle distributions of pions were measured with a spherical mirror system and a phototube array placed at the focal plane of the mirror. The measurements were repeated at various momentum thresholds by changing the index of refraction of the gas [3].

The experiment used a near detector (ND), which has been placed at 300 m from the production target to measure various types of neutrino interactions. ND consists of a 1000 ton water Cherenkov detector (1KT) and a fine grained detector system. The latter consists of a water-scintillating fiber tracking detector (SciFi) [6], lead glass counters (LG), and a muon range detector (MRD) [7]. In 2003, LG was replaced with a new fine segmented scintillation counter (SciBar) [8] to improve sensitivities for low energy neutrinos. The SciBar detector also has a capability to separate proton from π and μ.

Water Cherenkov detectors (SK and 1KT) are based on the same detector technique and most of the systematic errors (neutrino cross sections, detector efficiencies for various interaction modes, solid angle coverage for neutrino interactions) cancel after taking the ratio of the number of events in the 1KT and SK. Neutrino interactions in MRD were used to monitor the beam stability, taking advantage of its large fiducial mass. The interaction vertex distributions were used to monitor the directional stability of the neutrino beam within 1 mr. The stability of the neutrino spectrum was monitored by the energy and angular distributions of muons from CC neutrino interactions in MRD. Data from the fine grain detector gave a constraint on CCQE and nonQE interactions ratio, which was one of the unknown quantities in obtaining the neutrino flux from the observed events in ND.

The spectrum of the neutrino beam at the ND position has been obtained by fitting the two dimensional distributions of momentum and angle of muons by those predicted by a neutrino interaction model [9–12]. The distributions for various event categories i.e. CCQE enriched, nonQE enriched samples in each ND detectors, were fitted simultaneously. The result is compared with the expectation from a beam Monte Carlo in Figure 3.

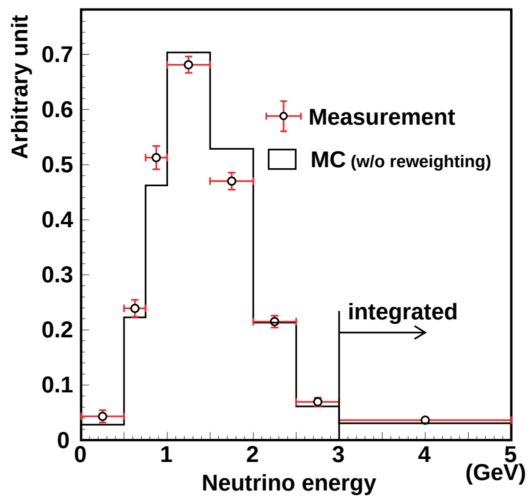

FIG. 3: The neutrino flux at ND, obtained by fitting (p_μ, θ_μ) distribution at ND, compared with the beam Monte Carlo expectation.

The beam at SK was predicted based on the extracted neutrino flux at ND.

The far to near ratio of spectrum for each energy bin (F/N ratio) is shown in Figure 4, calculated by the beam

Monte Carlo in the absence of oscillation. The errors are estimated from the HARP measurement errors.

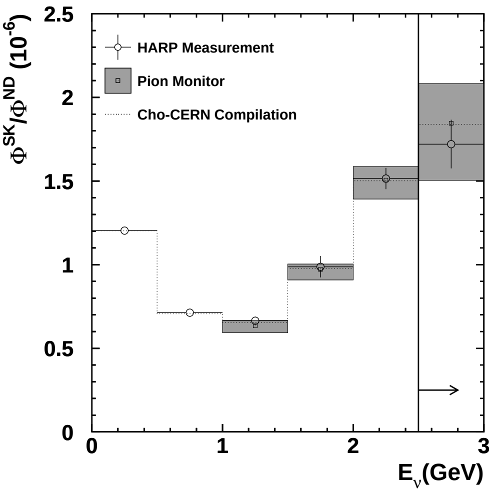

FIG. 4: Prediction for the K2K muon neutrino F/N ratio in the absence of oscillation.Figure includes the predictions based on the HARP measurements [4], PIMON measurements and Cho measurements in 1970 [5].

The events in SK are selected by requiring no entering particle from out-side and about 30 MeV electron-equivalent energy deposit in the inner detector of SK [2]. A clock referenced to the timing signal from GPS (global positioning system) is used for identification of the events. A requirement of the relative timing between extraction and detection at SK to be within the accelerator spill duration of 1.2 μs makes the estimated background to be 10^{-3}. A total of 112 events are identified as associated with the neutrino beam from KEK. For the spectrum analysis, 58 single muon like events (1Rμ) events in SK are used. The reconstructed neutrino energy is calculated by assuming that the event is CCQE and using the formula:

$$E_\nu^{rec} = \frac{m_N E_\mu - m_\mu^2}{m_N - E_\mu + P_\mu cos\theta_\mu}$$

where m_N, E_μ, m_μ, P_μ, and θ_μ are the nucleon mass, the muon energy, the muon mass, the muon momentum, and the production angle relative to the neutrino beam direction, respectively.

The oscillation analysis is performed by the maximum likelihood method. The expected beam at SK were first distorted for a given set of oscillation parameters $(\sin^2 2\theta, \Delta m^2)$, then the neutrino events were predicted by the neutrino interaction model, which was used in analyzing ND events. The likelihood is defined as $L = L_{norm} \times L_{shape}$. The normalization term $L_{norm}(N_{obs}, N_{exp})$ is the Poisson probability of observing N_{obs} events when the expected number of events is $N_{exp}(\Delta m^2, \sin^2 2\theta, f)$. The parameters f include the neutrino spectrum measured at the near detector, the F/N ratio, the reconstruction efficiency of SK for 1Rμ events (ϵ_{SK}), the QE/nonQE ratio, the ratio of measured to true neutrino energy, and the overall normalization. The first three errors are energy-dependent and correlated.

The shape term, L_{shape}, is the product of the probabilities of each 1Rμ event to be observed at $E_\nu^{rec}(= E_i)$: i.e.

$$L_{shape} = \Pi P(E_i, \Delta m^2, \sin^2 2\theta, f)$$

The likelihood is calculated at each point in the Δm^2, $\sin^2 2\theta$ parameter space.

All of the beam-induced events observed inside of the fiducial volume of SK are used to measure the reduction of the ν_μ flux. The expected number of FC events in SK without oscillation is estimated to be $158.1\,^{+9.2}_{-8.6}$. The major contributions to the errors on the expected number of events come from the uncertainties of the F/N ratio $\binom{+2.9\%}{-2.9\%}$ and the normalization $\binom{+4.9\%}{-4.8\%}$. The latter errors are mainly due to the vertex reconstruction both in the 1KT and in SK.

The maximum likelihood point is found to be at $(\sin^2 2\theta, \Delta m^2)$=$(1.19, 2.55 \times 10^{-3}\text{eV}^2)$. In the physical region, the best fit point is $(\sin^2 2\theta, \Delta m^2)$=$(1.0, 2.75 \times 10^{-3}\text{eV}^2)$. The observed E_ν^{rec} distribution of the 1Rμ is shown in Figure 5 together with the expected distribution for the best fit parameters of $(\sin^2 2\theta, \Delta m^2)$=$(1.0, 2.75 \times 10^{-3}\text{eV}^2)$.

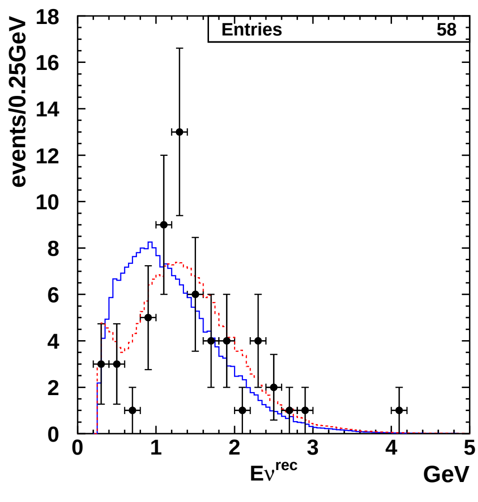

FIG. 5: The reconstructed E_ν distribution for SK events. The histogram with solid line is the expected spectrum shape without oscillation, which is normalized by the number of observed events. The histogram with dotted line is the one with best fit oscillation parameters.

At the best fit point in the physical region, the total number of predicted events in SK is 107.2, which agrees with the observation of 112 within statistical error. The consistency between the observed and the best fit E_ν^{rec} distributions is checked by the Kolgomov-Smirnov (KS) test. The KS probability is 37%, while for the null oscillation hypothesis it is 0.07%. The observation is consistent with the existence of neutrino oscillation. The probability that a measurement would get unphysical $\sin^2 2\theta$ greater than 1.2 is 26.2%.

Figure 6 shows the consistency of the results with the oscillation parameterization. Allowed regions of oscillation parameters evaluated with the reduction of events and one evaluated with the spectrum shape are shown separately. The figures show that both effects are consistent with the assumption of the neutrino oscillation parametrization.

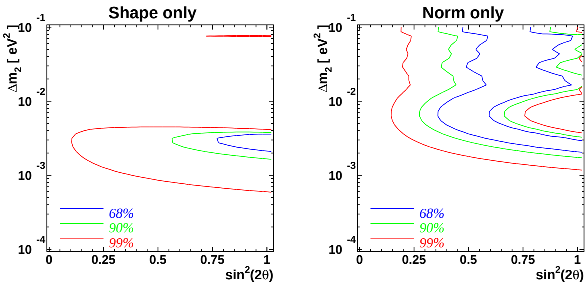

FIG. 6: Allowed regions of oscillation parameters evaluated with the reduction of events and one evaluated with spectrum shape are shown separately. The right hand side of the curves in the left plot and the bands between 2 same color curves in the right plot are the allowed regions. The consistency of the allowed regions indicates the validity of the parametrization of the neutrino oscillation analysis.

The allowed regions of the oscillation parameters are shown in Figure 7. The non-oscillation probability is calculated to be less than 0.0015% (4.3σ). The K2K experiment has confirmed the neutrino oscillation in the $\Delta m^2 \sim 3 \times 10^{-3}\mathrm{eV}^2$ region.

III. THE T2K EXPERIMENT

The K2K experiment has established the existence of the neutrino ocillation phenomena and accelerator can be effectively used to study neutrino oscillation. The Tokai-to-Kamioka (T2K) is an experiment in which a high intensity neutrino beam is produced at J-PARC [13] and detected by SK at 295 km [14]. This is a successor of the K2K experiment. The main goal of the experiment is to precisely measure neutrino oscillation phenomena. The experiment will use a narrow band beam, which can be produced by sending pions with an angle relative to the detector direction (off-axis beam). The advantages of the off-axis beam are intense low energy neutrinos, which are suitable for water Cherenkov technique, and a small high energy tail to minimize backgrounds from un-oscillating

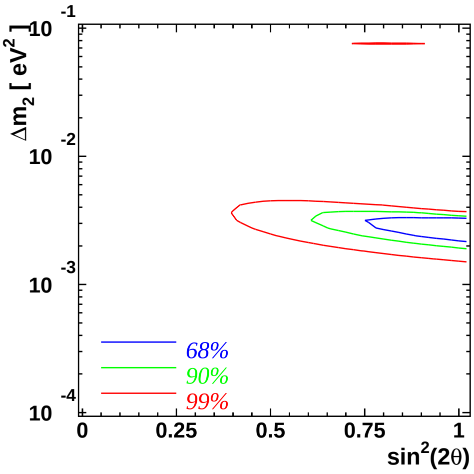

FIG. 7: The allowed regions of oscillation parameters by K2K whole data combining the results from event reduction and the spectrum distortion. The right hand side of the curves are allowed.

neutrinos. One of the most important goals is to look for unexpected phenomena with highest possible energy resolution.

Also a factor of 20 improvement of the sensitivity for the search of the mixing angle θ_{13} over the present upper limit. The goal is to extend the search down to $\sin^2 2\theta_{13} \simeq 2\sin^2 2\theta_{\mu e} > 0.008$. The mixing angle θ_{13} is the last unknown in the three flavor framework. If it is large enough to be detected at T2K, a future CP violation search in the neutrino sector becomes practical.

Another goal is precision measurements of the oscillation parameters in ν_μ disappearance. Observation of the oscillation minimum, a 1% measurement of the mixing angle and a 3% measurement of Δm^2 ($\delta(\Delta m^2_{23}) = 10^{-4}$ eV^2 and $\delta(\sin^2 2\theta_{23}) = 0.01$), may show the mixing of second and third generation neutrinos to be consistent with maximal at 1% accuracy. This may impose a constraint on the quark-lepton unification.

Also a search for sterile components in ν_μ disappearance is envisaged by detecting the neutral-current events. If a non-zero sterile component is found, the physics of fermions will need modification to accommodate extra member(s) of leptons.

The layout of the neutrino beamline in the J-PARC facility is illustrated in Figure 8 [13].

The proton beam extracted from the J-PARC 50-GeV PS toward inside the ring is bent about 90° by 28 superconducting combined function magnets and delivered to the production target in ~ 4.2 μs spill width with 3.3×10^{14} ppp at a $2 \sim 3.5$ s repetition cycle. The production target is a graphite rod of 26 mm diameter and 90 cm long (corresponding to 2 interaction length). About 80% of incoming protons interact in the target. The target receives 58 kJ/spill energy deposit by ioniza-

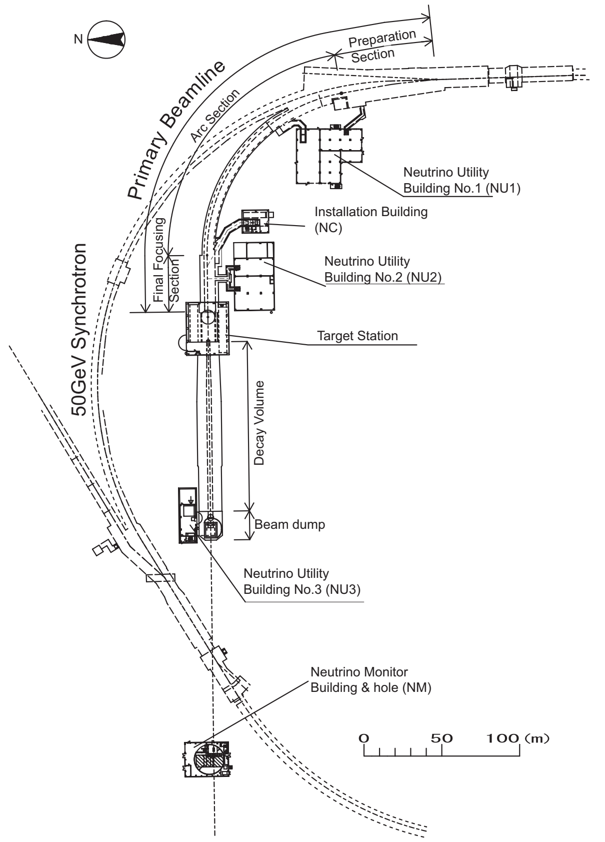

FIG. 8: The layout of neutrino facility in J-PARC.

tion losses of charged particles and it causes the thermal shock stress of ∼7 MPa. The heat is removed by forced-flow Helium gas and the stress is confirmed to be a factor 3 less than the strength of the graphite. The target is followed by three electromagnetic horns operated at 320 kA pulsed current to focus positively charged secondaries to the forward direction. They are cooled by water spray to remove the Joule heat and deposited energy by charged particles. Pions and kaons decay in flight into neutrinos in a decay volume (DV) of 110 m long (from target) placed just downstream of the horn, filled with Helium gas. The decay pipe is designed to accommodate the beam of $2 \sim 3°$ off-axis angle. The beam dump is placed at the end of DV and stops particles other than neutrinos. The dump consists of graphite blocks of about 3.15 m thickness followed by iron plates with 2.5 m total thickness. A muon monitor is placed just after the beam dump to monitor the intensity and the profile of muons which pass through the beam dump spill-by-spill. High energy muons of > 5 GeV can penetrate the beam dump and reach the muon monitor. At 280 m from the production target, neutrino detectors will be placed in order to measure neutrino beam properties. Two independent detector systems on the proton beam axis and off-axis (pointing to SK) are currently planned. The main purposes of the on-axis detector is to monitor the neutrino beam direction, intensity while the off-axis detector aims to measure energy spectrum, contamination of electron neutrinos and neutrino interactions with a similar energy spectrum at SK.

The expected ν_μ spectrum at SK without oscillation is plotted in Figure 9 [14]. The ν_e to ν_μ flux ratio is as small as 0.4% at the peak of ν_μ spectrum. The expected numbers of interactions at SK with 2.5° off-axis, where the peak energy is at 0.6 GeV, is 1,700 for CC interactions in fiducial volume of 22.5 kt in 1 year with 30 GeV, 0.75 MW, 3,000hr/yr operation.

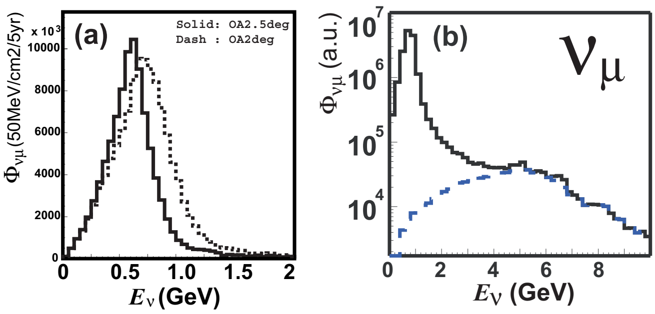

FIG. 9: Expected neutrino spectra. (a)Energy spectra of ν_μ fluxes for different off-axis angle with 30 GeV, 0.75 MW, 3,000 hr/yr operation. (b) ν_μ flux. Solid is total and dashed line is a contribution from kaon decay.

The construction of the neutrino facility started in April 2004 as a 5-year project, expected to be completed in March 2009.

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