NEUTRINO OSCILLATION IN THE K2K EXPERIMENT*

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This paper summarizes final results of the K2K experiment which probes neutrino oscillation on accelerator produced neutrino beam sent over 250 km baseline toward the Super-Kamiokande detector. K2K collected 9.2×10^{19} protons on target during its operation from 1999 to 2004. A total number of 112 beam induced neutrino events have been detected while $155.9^{+11.5}_{-10.2}$ events were expected for no oscillation scenario. Incorporating into analysis a distortion of neutrino energy spectra an allowed region of $1.9 \times 10^{-3} < \Delta m^2 < 3.5 \times 10^{-3}$ eV^2 was obtained for $\sin^2 2\theta = 1.0$ in agreement with atmospheric neutrino results. A limit for transformation of muon neutrino into electron neutrino has been achieved at $\sin^2 2\theta_{13} < 0.26$ from one detected shower like data event.

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1. Introduction

Existence of neutrino oscillations have already been observed by various experiments implying that neutrinos are not massless particles. For the first time the Super-Kamiokande experiment found a significant path-length dependent deficit in the flux of atmospheric ν_μ and announced their results at *Neutrino Conference* in 1998 [1,2]. Since then more precise measurements were carried by the Super-Kamiokande (SK) collaboration giving the value of $1.5\times10^{-3} < \Delta m^2 < 3.4\times10^{-3}$ eV^2 and limit $\sin^2 2\theta > 0.92$ [3]. Experiments on solar neutrinos have found deficits of electron neutrinos with respect to the prediction of the Solar Model. Thanks to the SNO results [4] electron

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neutrinos from the Sun have been proved to transform to $\nu_{\mu\tau}$. Combined analysis of SK, SNO and KamLAND data results with $7 \times 10^{-5} < \Delta m_{12}^2 < 9 \times 10^{-5}$ eV^2 and $0.2 < \sin^2\theta_{12} < 0.4$ [5,6].

Two different scales of mass square differences indicate existence of three neutrinos. Within framework of three neutrinos their flavor states are related to the three mass states by the Maki–Nakagawa–Sakata matrix which can be parametrized by three mixing angles, and CP violation phase [7]. Measurements of atmospheric and solar neutrinos allow to determine two mixing angles θ_{23} and θ_{12} respectively. Little is known about the third mixing angle θ_{13}. Non-observation of a disappearance of reactor $\overline{\nu}_e$ over a few kilometers baseline in the CHOOZ experiment allowed to derive a limit on θ_{13} to be smaller than 12 degrees [8].

The KEK to Kamiokande (K2K) experiment was designed to verify the nature of oscillation observed in the atmospheric sector. K2K was the first experiment which uses an accelerator produced neutrino beam with a long baseline between the production of the neutrinos and their detection. It searched for neutrino oscillation by observation of ν_μ disappearance in almost pure ν_μ beam. Thanks to ability to distinguish between muons and electrons in the far detector also a search for electron neutrino appearance is performed. Probabilities of neutrino oscillations for the study done by K2K experiment can be written in terms of the mixing angle and the difference of the mass squares as ($\Delta m^2 \gg \Delta m_{12}^2$):

$$\begin{aligned} P_{\nu_\mu \to \nu_\mu} &= 1 - \sin^2 2\theta \sin^2\left(1.27\frac{\Delta m^2 L}{E}\right), \\ P_{\nu_\mu \to \nu_e} &= \sin^2 2\theta_{\mu e} \sin^2\left(1.27\frac{\Delta m^2 L}{E}\right), \end{aligned}$$

where L is the baseline in km, E neutrino energy in GeV and mixing angles can be expressed as $\sin^2 2\theta \sim \cos^4\theta_{13}\sin^2 2\theta_{23} \sim \sin^2 2\theta_{23}$ or $\sin^2 2\theta_{\mu e} \sim \sin^2\theta_{23}\sin^2 2\theta_{13} \sim 1/2\sin^2 2\theta_{13}$.

Disappearance of the muon neutrinos is studied by taking into account a difference between observed and expected number of neutrino interactions and a distortion of the neutrino spectrum, while the search for electron neutrino appearance is based on a number of observed events associated with electron. As a consequence of the small value of $\theta_{13} < 12$ deg the ν_e appearance search is limited by statistics. However, the K2K data give the first chance to look for the appearance of electron neutrinos in accelerator produced neutrino beam.

This paper summarizes results from entire K2K data sample collected from 1999 to 2004 which corresponds to accumulated 9.2×10^{19} protons on target (p.o.t.) in total [9]. There were two running periods during the K2K operation: K2K-I (4.8×10^{19} p.o.t.) during which SK was instrumented with nominal 11,146 50 cm photomultiplier tubes. K2K-II (4.4×10^{19} p.o.t.) corresponds to the period of data taking after SK was rebuilt with 47% remaining photomultiplier tubes following an accident.

2. Overview of K2K experiment

The neutrino beam used in K2K experiment is a wide band neutrino beam with spectrum peaked about 1 GeV. Every 2.2 s a primary proton beam of the kinetic energy of 12 GeV is fast extracted from the KEK Proton Synchrotron making 1.1 μs beam spill. From the proton interaction on the aluminum target a positively charged particles, mainly π^+ are focused by 2-horn magnet system into a 200 m long decay pipe (see Fig. 1). Neutrinos are produced following pion decay $\pi^+ \to \nu_\mu + \mu$. The neutrino beam is almost pure, 98% , ν_μ beam with 1.3% , 1.2% and 0.018% contamination of ν_e , $\overline{\nu}_\mu$ and $\overline{\nu}_e$, respectively [10].

Understanding of the beam composition is important, especially the electron neutrino component of the beam which produces the background for the $\nu_\mu \to \nu_e$ appearance search. Moreover to predict neutrino beam at the far site an extrapolation of the measured neutrino spectrum at the near site to the far site is necessary. For this near to far extrapolation the beam

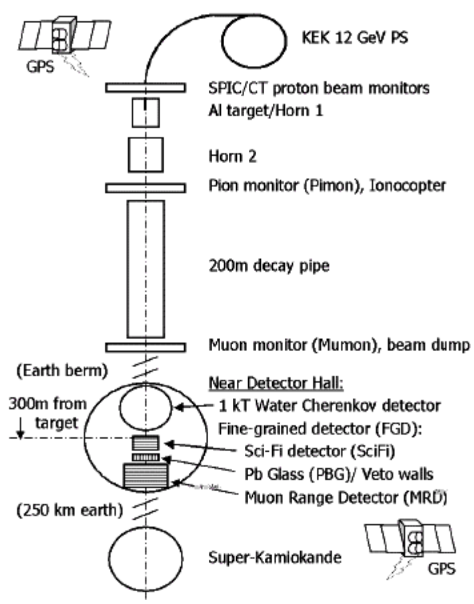

Fig. 1. Schematic view of the K2K experiment.

Monte Carlo simulation is used. It is based on GEANT with description of materials, magnetic field and geometry in the target production region. As an input it uses measurement of primary beam profile. In order to check the correctness of the beam Monte Carlo simulation, a pion momentum and divergence are measured by gas-Cerenkov pion monitor [11]. This detector was inserted occasionally on the secondary beam line downstream of the second horn. Fig. 2 shows results of the far to near flux ratio derived from the pion monitor measurement in comparison with the ratio predicted by the beam Monte Carlo. Prediction of the neutrino spectrum below energy of 1 GeV has not been verified by this measurement. The refractive index of the noble gas used by the pion monitor corresponds to the threshold of 2 GeV/c for pions and therefore the collected data cover the region with higher pion momenta only. To verify the pion production in lower energy region the KEK target was measured on the CERN 12.9 GeV proton beam by the HARP experiment [12]. The far to near ratios calculated using HARP data is presented in Fig. 2 and show an agreement within the measurement error with the beam Monte Carlo prediction. The HARP results are going to be incorporated into the final K2K analysis [10].

Energetic muons from pion decays are sampled by muon monitor detector (MUMON) and ensure monitoring of the beam in a real-time. MUMON is located after the beam dump, therefore only muons of $P_\mu > 5.5$ GeV/c can penetrate through the iron and concrete shields.

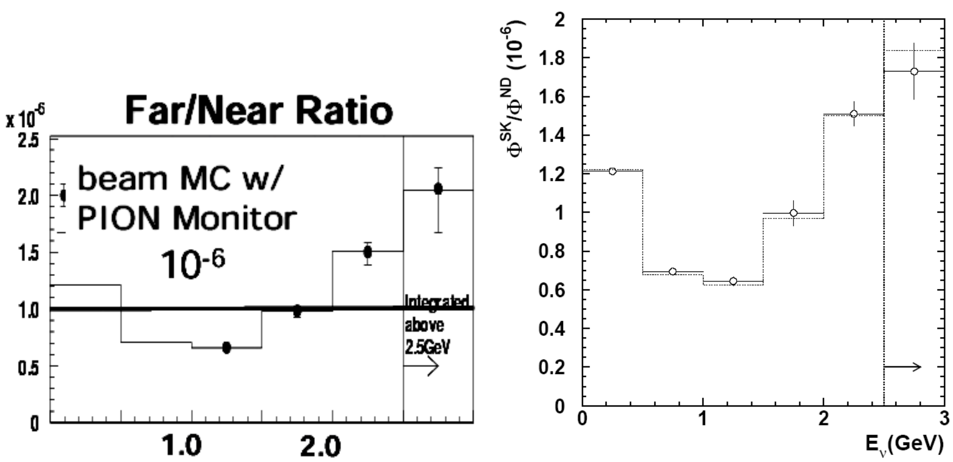

Fig. 2. The far to near flux ratio. The histograms result from the beam Monte Carlo simulation and the points are derived from the pion monitor (left) and HARP (right) data.

Near detectors are located in an underground experimental hall 300 m down from the production target. At first the neutrino beam passes through one kiloton water Cerenkov detector (KT) which is a scaled down version of the far detector, Super-Kamiokande (SK). The KT detector is equipped with 680 photomultiplier tubes which ensure 40% photocathode coverage. Neutrino flux measured by KT is used to predict expected number of events in the SK site in the absence of oscillation, since the same technology used in the near and far detectors allows for partial cancellation of systematic uncertainties. Then neutrino interactions are observed by the set of Fine Grain Detectors (FGD) with complementary capability to the KT. A scintillating fiber detector (SciFi) [13, 14] consisting of 6ton of water target and fully active solid scintillator-bar array (SciBar) [15] provide a better discrimination power between different types of interactions such as quasi elastic or inelastic. Downstream of the SciFi there was a lead glass calorimeter for tagging electromagnetic showers. It has been removed after 2001 and replaced with the SciBar since 2003. FGD is completed with the muon range detector (MRD) [16] made of 12 iron plates instrumented with drift tubes. Because of its large mass MRD can measure momentum of the contained muons and monitor stability of their directions. Direction of the beam was measured to be stable within 1 mrad during the whole period of data taking, while 3 mrad precision in the beam direction is required to ensure a constant neutrino spectrum at the far detector Super-Kamiokande located 250 km away from the KEK. More details concerning equipment of SK and its operation can be found in [17].

3. Measurement of neutrino flux in near detector

Near detectors provide valuable information about cross sections of inclusive single pion production measured by various sub-detectors and published in [18–20]. However, they are mainly dedicated to measure ν_μ spectrum before neutrinos oscillate.

Neutrino energy spectrum is measured by analyzing two dimensional distributions of reconstructed muon momenta (P_μ) and angles calculated with respect to the ν beam direction (θ_μ) in the KT, SciFi and SciBar detector systems. KT provides a sample of charge current ν_μ interactions down to 200 MeV/c of muon momenta, but it has low efficiency to reconstruct muons with momentum above 1.5 GeV/c since they exit the detector. On the contrary SciFi and SciBar have good efficiency to reconstruct muons above 1 GeV/c and thanks to their ability to detect protons they are able to separate QE and non-QE interactions better than KT (see [9] for details). A χ^2 fit method is adopted to compare ν data against the Monte Carlo expectation [10]. Two dimensional distributions of (P_μ,θ_μ) are prepared for eight

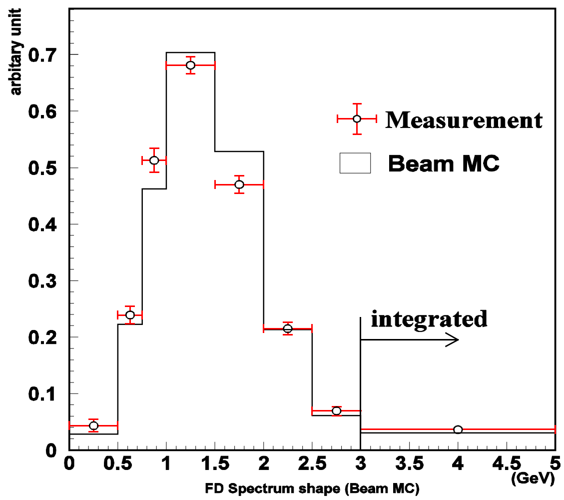

Fig. 3. Reconstructed neutrino energy spectrum measured by near detectors (dots) compared to prediction of the beam Monte Carlo (histogram).

neutrino energy bins of QE and non-QE Monte Carlo samples of each detector. During the fit a spectrum shape and non-QE to QE ratio are changed to find a minimum χ^2. The resulting neutrino spectrum of three detectors fit is shown in Fig. 3 in comparison to the prediction based on the beam simulation.

4. Event selection in the far detector

K2K beam induced events in SK are searched in 1.5 μs time window defined by comparing the Global Positioning System (GPS) time stamps of 1.1 μs proton beam spill at KEK. Reconstruction algorithms and selection criteria applied to SK events are the same as those used in atmospheric neutrino analysis [21]. Only events with total deposited energy greater then 30 MeV and reconstructed vertex inside a fiducial volume of 22.5 kt are chosen for the analysis. For entire statistics of the experiment 112 fully contained events associated with the K2K beam in SK fiducial volume are observed. 58 of them are identified as single ring μ-like events. They are used for the spectrum analysis of ν_μ disappearance.

To extract electron neutrinos from the events induced by the K2K beam we search for charge current quasi elastic interactions. Therefore single ring e-like events are used as a signature for ν_e search. However, this sample contains a large background of ν_μ interactions, mainly with a π^0 production via neutral current processes. High energy $\pi^0 \to \gamma\gamma$ may mimic an electron event when one gamma only is found by standard reconstruction program. A special dedicated program has been developed to search for hidden gammas from π^0 decay. It allows to reduce π^0 background from about 90% to 30% keeping the ν_e finding efficiency of 50% (more details can be found in [22]). As a result that only one event in the whole K2K data sample passed criteria for selection of ν_e interaction candidates. It is consistent with the expected background composed of 0.4 events from the ν_e beam contamination and 1.3 e-like events originated from ν_μ interactions. Contamination of ν_e in the beam is modeled from the beam Monte Carlo simulation, which has been verified by the measurements of the lead glass calorimeter and the SciBar detector at the KEK site [22–24].

5. Search for $\nu_\mu \to \nu_\mu$ disappearance

A two flavor oscillation analysis of ν_μ disappearance is performed adapting the maximum-likelihood method. This analysis uses two independent approaches which finally are combined into the global fit. The first compares the total number of beam neutrino induced events in fiducial volume of SK with the expected number of events, $N_{\rm exp}^{\rm SK}$, in the absence of neutrino oscillation. In order to predict number of events in the far site the KT measurement is extrapolated 250 km away using the far to near spectrum ratio. Method of the calculation is described by the following formula:

$$N_{\rm exp}^{\rm SK} = N_{\rm int}^{\rm KT} \frac{\int \Phi^{\rm SK}(E_\nu)\,\sigma(E_\nu)dE_\nu}{\int \Phi^{\rm KT}(E_\nu)\,\sigma(E_\nu)dE_\nu} \frac{M_{\rm SK}}{M_{\rm KT}} \frac{\rm POT_{SK}}{\rm POT_{KT}} \frac{\varepsilon_{\rm SK}}{\varepsilon_{\rm KT}}\,,$$

where $\rm POT_{SK/KT}$ is a number of protons on target corresponding to the samples used in the SK/KT analysis, $\varepsilon_{\rm SK/KT}$ is the efficiency to detect neutrinos, with $\Phi^{\rm SK/KT}$ being a neutrino energy spectrum in SK/KT of mass $M_{\rm SK/KT}$; the dependence of neutrino interaction cross section $\sigma(E_\nu)$ on its energy is also taken into account. The 112 events observed in the SK detector in comparison to the obtained number of $155.9^{+11.5}_{-10.2}$ expected events shows 3.1σ deficit of beam ν_μ.

The second approach of the analysis is based on the fact that neutrino energy spectra are sensitive to oscillation parameters. Here the measurement of the neutrino energy spectra done by the near detectors is used to predict a neutrino spectrum at the SK site. As for the calculation of the expected number of events a far to near spectrum ratio based on beam Monte Carlo simulation (Fig. 2) is used for spectrum extrapolation. Only the single ring μ-like events are chosen in order to select charge current quasi-elastic interactions. The neutrino energy can be easily estimated from the muon kinematics as:

$$E_\nu = \frac{m_N E_\mu + m_\mu^2/2}{m_N - E_\mu + p_\mu \cos\theta_\mu}\,,$$

where m_N represents nucleon mass, with m_μ, E_μ, P_μ, θ_μ being a muon mass, energy, momentum and angle.

Consequently the likelihood function to be maximized contains two terms resulting from the event rate and the spectrum shape analysis and one additional term which accounts for the systematic uncertainties. The results indicate Δm^2 between 1.9×10^{-3} and 3.5×10^{-3} eV^2 (90% C.L.) for the physical region of $\sin^2 2\theta = 1.0$ as shown in the left plot of Fig. 4. The observed distribution of reconstructed neutrino energy spectrum is presented on the right plot of Fig. 4 with overlaid histograms for expected spectrum in no oscillation scenario and the spectrum obtained for the best fit parameters. Taking into account information of reduced number of events and spectrum shape a no oscillation hypothesis can be rejected at 99.8% confidence level.

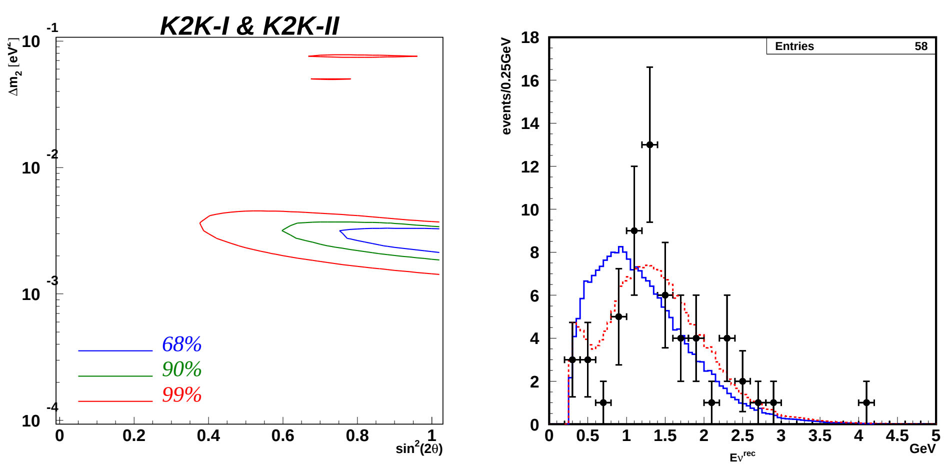

Fig. 4. Left — allowed region of oscillation parameters Δm^2 and $\sin^2 2\theta$; right — reconstructed spectrum of neutrino energy for 58 μ-like selected events (dots) compared with expectation of neutrino spectra for non-oscillation scenario (continuous histogram) and the best fit parameter of $\Delta m^2 = 2.8\times10^{-3}$ eV^2 (dashed histogram). Both plots correspond to entire data sample of K2K. All the curves are area normalized.

6. Search for $\nu_\mu \to \nu_e$ appearance

For a study of electron neutrino appearance a two flavor analysis is performed based on the comparison of the number of observed events against expected background. After a series of cuts (see [22] for details) one observed event in the data has been selected while a total value of $1.7^{+0.6}_{-0.4}$ expected background events are predicted. An appearance signal was searched for as a function of two parameters, the mixing angle and the mass square difference, using the Poisson distribution. The systematic uncertainty in the expectation of ν_μ-originated background of 1.3 event is $^{+39}_{-24}\%$ or for ν_e beam contamination of 0.4 event is $^{+32}_{-21}\%$, although this analysis is dominated by statistical error. The resulting excluded contour is shown in Fig. 5. For the atmospheric $\Delta m^2 = 2.8 \times 10^{-3}$ eV^2 a ν_μ to ν_e transformation is excluded for $\sin^2 2\theta_{\mu e} > 0.13$ at 90% C.L. Our limit corresponds to $\sin^2 2\theta_{13} < 0.26$, while the current most stringent limit of $\sin^2 2\theta_{13} < 0.1$ comes from the reactor CHOOZ experiment [8].

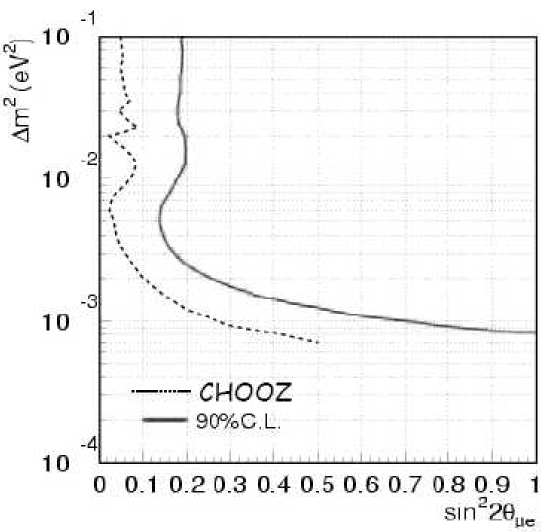

Fig. 5. The upper bound on $\nu_\mu \to \nu_e$ oscillation parameters obtained from K2K at 90% C.L. compared to the CHOOZ results. Region on the right from the curve corresponds to the excluded parameters values.

7. Summary

The K2K collaboration as the first in the neutrino history faced an operation and understanding of collected data from an accelerator produced neutrinos which travel a long distance to be detected by the Super-Kamiokande detector. During its operation from 1999 to 2004 the experiment collected 9.2×10^{19} protons on target which allow to give evidence for ν_μ oscillation in the atmospheric region by measuring $1.9 \times 10^{-3} < \Delta m^2 < 3.5 \times 10^{-3}$ eV^2

for $\sin^2 2\theta = 1.0$. Also the first attempt was done toward the search for electron neutrinos oscillated from muon neutrino beam. Here the limit for $\sin^2 2\theta_{13} < 0.26$ has been derived. Currently many experiments, reactor (*e.g.* Double Chooz [25]) or accelerator based, with high intensity neutrino beam (as T2K [26] and NOνA [27]) are planned to allow precise probing of oscillation parameters. The largest interest is focused on the measurement of the less known θ_{13} and a chance to observe CP violation phase in the neutrino sector. Recently the MINOS collaboration [28], the second operating long baseline experiment probing the ν_μ disappearance has presented their first results based on collected 9.3×10^{19} p.o.t. during its operation since May until December of 2005. The parameters $\Delta m^2 = 3.05^{+0.60}_{-0.55}(\mathrm{stat}) \pm 0.12(\mathrm{syst}) \times 10^{-3}$ eV^2 and $\sin^2 2\theta = 0.88^{+0.12}_{-0.15}(\mathrm{stat}) \pm 0.06(\mathrm{syst})$ measured by MINOS [29] are consistent with Super-Kamiokande atmospheric and K2K beam induced results and show that more precise measurements are right a round the corner.

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