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# RECENT RESULTS OF K2K EXPERIMENT*

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K2K long-baseline experiment is the first attempt to test atmospheric neutrino oscillation results under controlled beam conditions. It was found that the whole collected data sample disfavor no oscillation hypothesis at $4\sigma$ level. The full oscillation analysis of $\nu_\mu \to \nu_x$ and $\nu_\mu \to \nu_e$ transformations was performed using data set collected from June 1999 to July 2001. As a result we derive allowed region at 90% CL of $\Delta m^2 = 1.5 - 3.9 \times 10^{-3}$ eV$^2$ for $\sin^2 2\theta_{\mu\tau} = 1$ consistent with atmospheric neutrino results. For $\nu_e$ appearance search, an one observed event remains consistent with $2.4 \pm 0.6$ background expectation. This allowed to obtain upper limit at 90% CL of $\sin^2 2\theta_{\mu e} < 0.15$ for the best-fit $\Delta m^2$ from $\nu_\mu$ disappearance analysis of $2.8 \times 10^{-3}$ eV$^2$.

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## 1. Introduction

One of the most fundamental questions reaching beyond the Standard Model is whether neutrinos are massive particles. Searches for neutrino oscillations provide a technique which allows to probe neutrino masses below 1 eV scale. Results from last few years of atmospheric and solar neutrinos indicate existence of non-zero neutrino masses. The aim of KEK to Kamioka long baseline accelerator experiment (K2K) is to provide an independent check of the atmospheric neutrino results under controlled beam condition. Parameters of the K2K experiment search as the neutrino energy spectrum peaked at 1 GeV and baseline of 250 km are designed to probe region of $\Delta m^2 \sim 3 \times 10^{-3}$ eV$^2$ with maximum mixing angle of atmospheric neutrino

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oscillation [1]. Such low beam energy in the K2K experiment implies that $\nu_\mu \rightarrow \nu_x$ oscillation can be studied only in $\nu_\mu$ disappearance mode, since a production of tau lepton is not energetically accessible. On the other hand a precise understanding of beam composition and a possibility of particle identification in water Cherenkov detector allows us to examine $\nu_\mu \rightarrow \nu_e$ oscillation case with a search for $\nu_e$ appearance signal.

## 2. Design of K2K neutrino beam and detectors

The K2K horn-focused wide-band $\nu_\mu$ beam is originated by a primary 12 GeV energy protons from the KEK Proton Synchrotron. Every 2.2 s about $6 \times 10^{12}$ protons form a 1.1 $\mu$s beam pulse composed of 9 bunches. Positive pions originated from interactions of protons at 30 mm diameter, 66 cm long aluminum target, are focused by pair of horn magnets operated at 250 kA. Neutrino beam mainly comes from $\pi^+ \rightarrow \nu_\mu \mu^+$ decays inside 200 m long decay tunnel, while muons are stopped in a dump. Spill-by-spill monitoring of the beam direction is assured by ionization chambers and an array of silicon pad detectors (muon monitor) located downstream of the dump. Stability of 1 mrad is achieved while 3 mrad stability is required. Properties of the neutrino KEK beam are given in Table I. The neutrino fluxes and flavor beam composition are derived from Monte Carlo (MC) beam simulation [2]. Information of the beam MC simulations such as pion kinematics are verified by a pion monitor — ring imaging gas Cherenkov counter put occasionally in the beam [3]. The K2K beam is almost pure: 98% of neutrinos are $\nu_\mu$. An estimated 1.3% $\nu_e$ beam contamination has to be checked independently. It is important to estimate expected $\nu_e$ background in the far detector for $\nu_\mu \rightarrow \nu_e$ oscillation analysis.

The neutrino beam passes through the Front Detectors located at KEK site and is sent to far Super-Kamiokande (SK) 50 kiloton water Cherenkov

TABLE I

Properties of the neutrino KEK beam

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| | |
|---|---|
| beam composition $\nu_\mu$ | 98.2% |
| $\nu_e$ | 1.3% |
| $\bar{\nu_\mu}$ | 0.5% |
| mean $\nu_\mu$ energy | 1.3 GeV |
| peak $\nu_\mu$ energy | 1.0 GeV |
| flux at near site | $1.7 \times 10^{12} \nu/\mathrm{cm}^2$ for $10^{20}$ p.o.t. |
| flux at far site | $1.3 \times 10^{6} \nu/\mathrm{cm}^2$ for $10^{20}$ p.o.t. |

detector [4] dedicated to study effects of the oscillation. The Front Detectors (Fig. 1) has two components, the 1 kiloton (1KT) water Cherenkov detector and fine-grain detector (FGD). FGD consists of the scintillating fiber detector (SciFi), veto scintillation counters, lead glass calorimeter (LG)[1] and muon range detector (MRD). Information from the Front Detectors are used to calculate absolute flux prediction and expected neutrino energy spectrum in the far detector. The FGD provides good precision to separate quasi (used for energy spectrum measurement) and non-quasi elastic interactions due to its high granularity. Additionally it is used for monitoring of neutrino direction and stability of the beam.

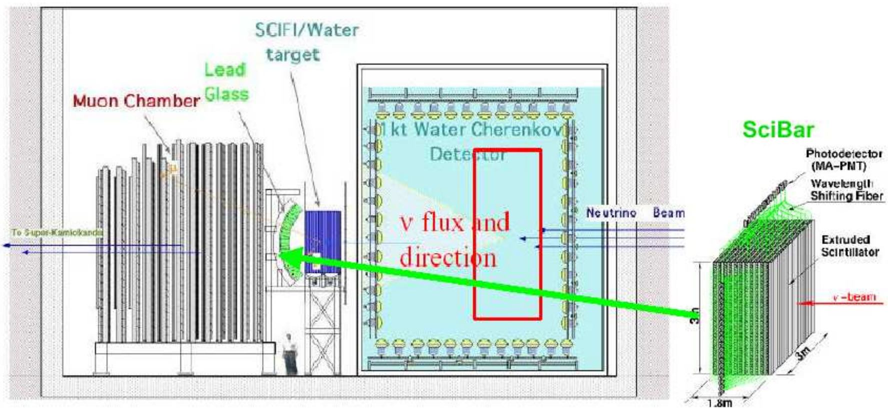


Fig. 1. Front Detectors at KEK site.

K2K as well as SK experiments are divided into two phases K2K-I (SK-I) and K2K-II (SK-II) corresponding to data taking periods before and after accident of SK detector on November 2001. The first phase of K2K corresponds to data taken from June 1999 to July 2001, while K2K-II sample contains data from January 2003 to April 2003. After rebuilding, the SK detector is taking data with about 50% of photo-cathode coverage comparing to the first phase of the experiment. Smaller PMT density is not detrimental to the K2K and atmospheric neutrino studies.

## 3. Detected and expected number of events at far detector

Neutrino interactions at the far detector are self-triggered. Data reduction for SK events associated with K2K beam uses the same procedure as is applied for the atmospheric neutrino data and additionally requires time correlation with the beam signal. To reject cosmic ray muons and events

[1] Currently replaced by solid scintillator tracking detector (SciBar) designed to detect low energy particles with high efficiency. It has started data taking from Oct. 2003.

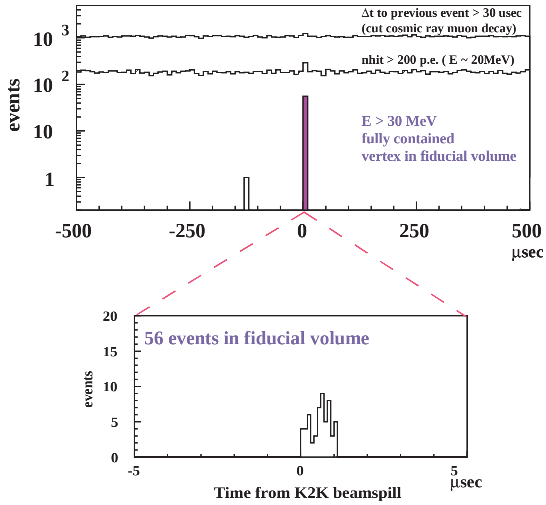


Fig. 2. The distribution of time difference between absolute detection time at SK site and the beam spill extraction time at KEK corrected by time of flight. The upper plot shows events in 1 ms search window after three reduction steps. The bottom one shows the distribution of the events within the peak around K2K beam spill.

exiting the inner detector, only events with no activity in outer detector are selected. Finally we require deposit energy greater then 30 MeV and fiducial volume for physical analysis of 22.5 kiloton (Fig. 2). The event selection is based on timing information about each beam spill using Global Positioning System. Time difference between absolute detection time at SK site and the beam spill extraction time at KEK corrected by time of flight on distance of 250 km should be distributed within interval 0 $\mu$s to 1.1 $\mu$s to match the spill width of 1.1 $\mu$s. With an accuracy of absolute time determination about 0.2 $\mu$s we expect good events in a window from $-0.2$ $\mu$s to 1.3 $\mu$s. As seen in Fig. 2 the initial searching time window of 1 ms has one event outside of the K2K beam timing. Observation of this event is in agreement with expected detection of atmospheric neutrino at this sample size. The expected number of atmospheric neutrino interactions within 1.5 $\mu$s K2K time window is of the order of $10^{-3}$. Therefore the selected events form a clear K2K beam associated event sample.

Number of events predicted to be observed in absence of neutrino oscillation is calculated based on measurement in the Front Detector. The 1KT measurements are used as a reference since they are based on the same detector technique and the same reconstruction algorithms as SK. This assures the same systematic error cancellation between near and far detector. To obtain predictions for SK the detected number of events at 1KT is corrected for difference in neutrino fluxes (based on MC beam simulation), different target masses, detection efficiencies and lifetime of SK and 1KT detectors.

Table II contains comparison of predicted and observed number of events at SK. It describes K2K-I and K2K-II experiments phases corresponding to $4.8 \times 10^{19}$ and $1.5 \times 10^{19}$ accumulated protons on target, respectively. Comparison of the observed number of 56 events with expected $80.1^{+6.2}_{-5.4}$ for K2K-I, as well as 16 events observed with $26^{+2.3}_{-2.1}$ expected for K2K-II disagree at 4 $\sigma$ level. This provides a clear evidence of $\nu_\mu$ disappearance. Additionally, both data taking periods show consistent rate reduction of $0.70 \pm 0.09$ and $0.61 \pm 0.15$.

TABLE II

Data summary.

| | K2K-I Jun'99–Jul'01 | K2K-II Jan'03–Apr'03 |
|---|---|---|
| p.o.t | $4.8 \times 10^{19}$ | $1.5 \times 10^{19}$ |
| Observed at SK | 56 | 16 |
| Expected from 1KT | $80.1^{+6.2}_{-5.4}$ | $26.4^{+2.3}_{-2.1}$ |
| Obs/Exp | $0.70 \pm 0.09$(stat) | $0.61 \pm 0.15$(stat) |

## 4. Results of oscillation analysis

### *4.1. Phenomenological introduction*

To describe neutrino oscillations one needs to consider neutrino mixing and mass difference of neutrino states. A transformation of neutrino mass eigenstates $\nu_1$, $\nu_2$, $\nu_3$ to flavor states $\nu_e$, $\nu_\mu$, $\nu_\tau$ participating in weak interactions is described by Maki–Nakagawa–Sakata matrix. It is analogous to the Cabibo–Kobayashi–Maskawa matrix in quark sector and can be parameterized by three mixing angles $\theta_1$, $\theta_2$, $\theta_3$ assuming CP conservation (Particle Data Group and Ref. [5]). Probabilities of neutrino oscillations are functions of differences of mass squares $\Delta m^2 = m_i^2 - m_j^2$ $(i,j = 1,2,3)$. Existence of three different neutrino flavors implies two independent $\Delta m^2$. Current results of atmospheric neutrinos give $\Delta m^2 \sim 10^{-3}$ eV$^2$, while solar and reactors neutrino measurements provide $\delta m^2 \sim 10^{-4}$ eV$^2$. This allows to derive oscillation probabilities assuming $\Delta m^2 \gg \delta m^2$:

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

where the frequency term depends on atmospheric $\Delta m^2$ only, neutrino path length $L$ and energy $E$. The factors $\sin^2 2\theta_{\mu\tau} = \cos^4\theta_{13}\sin^2 2\theta_{23}$, $\sin^2 2\theta_{\mu e} = \sin^2\theta_{23}\sin^2 2\theta_{13}$ describe effective mixing angles for $\nu_\mu - \nu_\tau$ and $\nu_\mu - \nu_e$ oscillations, respectively.

### *4.2. Muon neutrino disappearance*

In a search of neutrino flavor transformation under disappearance mode the overall flux suppression and energy spectrum distortion are expected. All neutrinos detected in SK associated with K2K beam are used to derive an event suppression (see Table II). For the study of neutrino energy spectrum only single ring events identified as muons are used. This sample is enhanced in charge current quasi-elastic events. Using information of reconstructed muon momentum and angle with respect to the known neutrino direction the neutrino energy can thus be reconstructed as:

$$E_\nu = \frac{ME_\mu + m^2}{M - E_\mu + p_\mu\cos\theta_\mu}\,,$$

where $M$ is nucleon mass, $m$, $E_\mu$, $p_\mu$ and $\theta_\mu$ are muon mass, energy, momentum and opening angle with respect to the neutrino beam direction. Neutrino energy spectrum measured by Front Detectors is extrapolated to the far detector and compared with energy spectrum obtained at SK site. Combined informations from 1KT and FGD neutrino spectrum in near site is used. Since 1KT has high efficiency to muons below 1 GeV and FGD has high efficiency for measuring muons above 1 GeV, those two detectors assure complete coverage of relevant energy range. The full error analysis using information from both front detectors is performed. Additionally, uncertainty of neutrino interaction model is taken into account on the base of near detector measurements. For overall oscillation analysis the maximum-likelihood method is used, which combines informations about number of events and shape of energy spectrum predicted and observed in SK. It also takes into account full error correlations. A detailed description of the strategy for $\nu_\mu \to \nu_x$ analysis can be found in Ref. [6, 7].

The whole K2K-I data sample is used in the oscillation analysis corresponding to $4.8\times10^{19}$ protons on target. The spectrum shape study discards the data taken in June and July 1999 (6.5% of K2K-I statistics) due to difference in beam configuration leading to different spectrum shape during this period.

Fig. 3-left presents the allowed parameter region in the $\Delta m^2$ and $\sin^2 2\theta_{\mu\tau}$ plane. The allowed region gives $1.5\times10^{-3} < \Delta m^2 < 3.9\times10^{-3}$ eV$^2$ for $\sin^2 2\theta_{\mu\tau} = 1$ at 90% CL. This is in agreement with SK-I atmospheric neutrino results [8]. Using the best fit parameters of $\Delta m^2 = 2.8\times10^{-3}$ eV$^2$ and

$\sin^2 2\theta_{\mu\tau} = 1$ the expected number of events in SK is 54 in good agreement with 56 events observed. Kolgomorov–Smirnov test gives 79% probability that the spectrum derived from data points is explained by the best-fit results (Fig. 3-right). On the other hand, combined results of event rate and spectrum shape give less than 1% probability for null oscillation scenario.

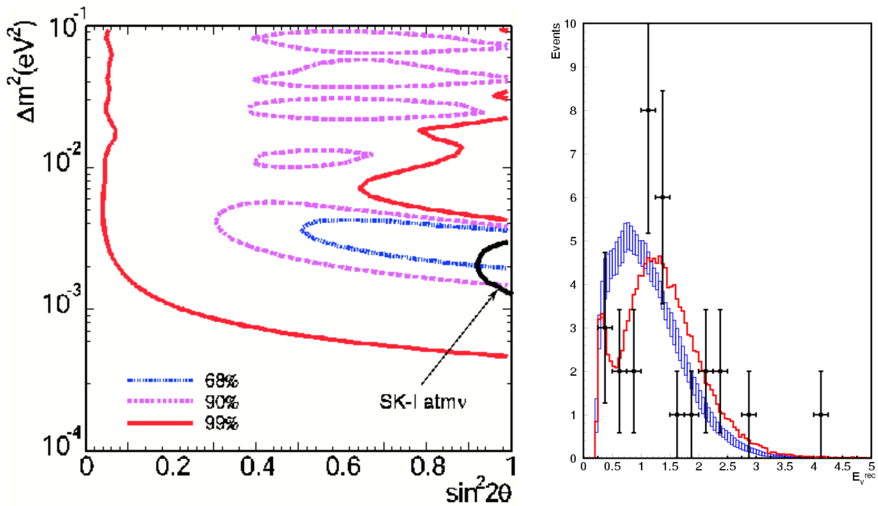


Fig. 3. Left: Allowed region in the $\Delta m^2$ and $sin^2 2\theta_{\mu\tau}$ plane. Dashed lines show 90% CL allowed region derived from K2K-I data and are compared to SK-I atmospheric neutrino results (black). Right: reconstructed neutrino energy spectrum. Points correspond to 29 single ring $\mu$-like events detected at SK, box histogram presents neutrino energy spectrum expected in null-oscillation scenario and solid histogram shows the best-fit spectrum. Both histograms are normalized to the number of observed 1 ring $\mu$-like events.

### *4.3. Electron neutrino appearance*

The strategy for electron neutrino search is based on observation of electron events above expected background. The challenging task in this analysis is to understand precisely the background. It consists of $\nu_e$ beam contamination originated from muon and kaon decays, and $\nu_\mu$ interactions which are classified as $e$-like events. The $\nu_\mu$ related background is dominated by Neutral Current interactions (about 90% of $\nu_\mu$ associated background) with $\pi^0$ in the final state. High energy $\pi^0$ is likely to be followed by two overlapped gammas identified as single ring $e$-like event. The selection criteria are the same as referred to the Section 3. At first fully contained events inside fiducial volume are selected. Then one selects single ring events, identified as $e$-like with visible energy larger than 100 MeV which are not followed by decay electron. Summary of data reduction is presented in Table III for data collected during K2K-I phase and MC sample using 1.3% $\nu_e$ beam contamination (see Section 2). One $\nu_e$ interaction candidate was observed in the far detector data sample while $2.4 \pm 0.6$ background events were expected [9]. The observation is thus consistent with background expectation, and no evidence for $\nu_e$ appearance signal has been observed. The upper limit on $\nu_e$ appearance signal results in the excluded region of parameters in Fig. 4. It is compared to the region excluded from $\bar{\nu_e}$ disappearance search in CHOOZ [10] experiment and allowed region from 3-flavor atmospheric neutrino analysis for SK-I. Assumption of the best-fit result from $\nu_\mu$ disappearance analysis $\Delta m^2 = 2.8 \times 10^{-3}$ eV$^2$ gives upper limit of $\sin^2 2\theta_{\mu e} < 0.15$ at 90% CL.

TABLE III

Reduction summary for $\nu_e$ search.

| | DATA | $\nu_\mu$ MC | $\nu_e$ MC |
|---|---|---|---|
| FCFV | 56 | 80 | 0.82 |
| 1 ring | 32 | 50 | 0.48 |
| $e$-like | 1 | 2.9 | 0.42 |
| $E_{\rm vis}$ >100 MeV | 1 | 2.6 | 0.41 |
| w/o decay-$e$ | 1 | 2.0 | 0.35 |

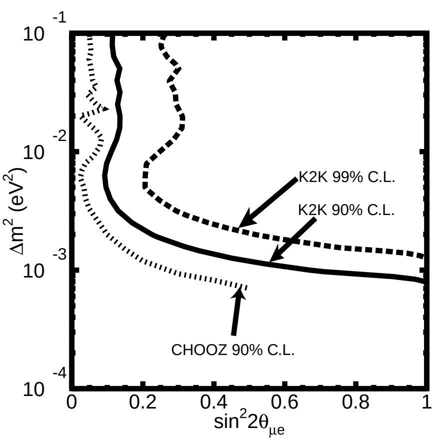


Fig. 4. Excluded region in the $\Delta m^2$ and $\sin^2 2\theta_{\mu e}$ plane. The right side of the solid (dashed) curve shows excluded region from K2K-I data at 90% (99%) CL, with comparison to CHOOZ results — dotted curve.

## 5. Summary

K2K is the first of several planned long-baseline accelerator experiments dedicated to study neutrino oscillations. It has been operated since June 1999 and resumed data taking in December 2002 after a successful reconstruction of Super-Kamiokande detector. The K2K-I as well as the K2K-II data disfavor no oscillation hypothesis at $4\sigma$ level. They provide independent confirmation of atmospheric neutrino results but with the use of well known energy spectrum of neutrino beam. In addition, K2K as a first experiment derives limit on $\nu_\mu \to \nu_e$ mixing angle ($\sin^2 2\theta_{\mu e}$) based on a search of electron neutrino.

We are planning to double current statistics of K2K-I and collect in total $10^{20}$ protons on target before April 2005. This will provide richer data set for energy spectrum study. In the more distant future the neutrino program is going to be continued by JPARC off-axis accelerator experiment [11]. A one order of magnitude more precise measurement of atmospheric $\Delta m^2$ is planned to be achieved and the sensitivity for $\nu_\mu \to \nu_e$ appearance search is expected to be 20 times better than in current experiments. Current neutrino programs are going toward complete understanding of neutrino mixing matrix and their masses. Consequently this will allow to test theories about origin of particle masses.

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