K2K (KEK to Kamioka) neutrino-oscillation experiment at KEK-PS

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A long-baseline neutrino-oscillation experiment using a well-defined neutrino beam is in preparation at KEK. Neutrinos generated at KEK will be detected by the Super-Kamiokande detector 250 km away. The design of the neutrino beam line, beam monitors and detector are briefly presented. The sensitivities for neutrino oscillations are also discussed.

§1. Overview

In recent years, several underground neutrino observatories\(^1\)\(^-\)\(^3\) have reported that the atmospheric neutrino ratio, \(R \equiv (\nu_\mu + \bar{\nu}_\mu)/(\nu_e + \bar{\nu}_e)\), is significantly smaller than the theoretical expectations. This “atmospheric neutrino anomaly” can be explained by a neutrino oscillation hypothesis with an oscillation parameter region of \(\Delta m^2 \sim 10^{-2}\text{eV}^2\) and \(\sin^2 2\theta \sim 1\). The atmospheric neutrino anomaly has also been confirmed by a preliminary result from the Super-Kamiokande experiment,\(^4\), which shows a rather smaller \(\Delta m^2\) than does Kamiokande.

The K2K experiment\(^5\) (formerly called the KEK-PS E362 experiment) is the first long-baseline neutrino-oscillation experiment using an artificial neutrino beam. The almost pure \(\nu_\mu\) beam from \(\pi^+\) decays is generated in the KEK 12-GeV Proton Synchrotron, and is directed toward the Super-Kamiokande detector, which is about 250 km away from KEK. The neutrino events observed in the Super-Kamiokande detector are compared with neutrino events in the front detector constructed at the KEK site. The nominal sensitive region on the neutrino-oscillation parameter is \(\Delta m^2 = 10^{-2}\text{eV}^2 \sim 10^{-3}\text{eV}^2\), which covers the parameter region suggested by the atmospheric neutrino anomaly.

§2. Neutrino beam

A neutrino beamline is under construction at KEK.\(^6\) A picture of the neutrino beamline under construction is shown in Figure 1.

A proton beam of 12 GeV is extracted from the Proton Synchrotron with a fast
extraction mode. The time width of one spill is 1.1$\mu$sec. The frequency of the beam is 1 spill per 2.2 seconds and the nominal intensity is about $6 \times 10^{12}$ protons/spill. A total of $1 \times 10^{20}$ p.o.t (protons on target) will be extracted in 3 years of operation.

The proton beam is bent by 94$^\circ$ by dipole magnets, and transported to an aluminum target of 2 cm$\phi \times$ 65 cm. Positively charged particles produced in the target are focused by a toroidal magnetic field produced by a pair of Horns toward the direction of the Super-Kamiokande detector. The nominal pulse current of the Horn is 250kA. The muon neutrino flux will be enhanced by a factor of 14 by installing the Horns. A test operation of the Horns was successfully completed in fall, 1997.

In a 200 m decay tunnel followed with the Horn magnets, one $\pi^+$ decays to one $\nu_\mu$ and one $\mu^+$. Muons and the remaining pions are absorbed in a beam dump downstream of the decay tunnel.

The generation of the neutrino beam is simulated using a Monte-Carlo simulation. The energy spectrum and angular dependence of the beam at the front detector (300 m downstream from the target) and at the Super-Kamiokande detector (250 km downstream) are shown in Figure 2. The mean energy of the neutrino beam is about 1.4 GeV, and the peak energy is about 1 GeV. The contamination of electron neutrinos was calculated to be $\sim$ 1%. The energy spectrum of the neutrino beam is uniform within an angular spread of 3 mrad from the center of the beam axis. Because the angular acceptance of the Super-Kamiokande detector from the KEK site is $\sim$ 50m/250km = 0.2 mrad, the divergence of the neutrino beam is much larger than the size of the Super-Kamiokande detector.

§3. Beam monitors

In order to obtain the neutrino-energy spectrum, a pion monitor will be set downstream of the second Horn. The pion monitor is a gas Cherenkov detector with a
spherical mirror and R-C318 gas. Charged pions emit Cherenkov light in the gas, and a Cherenkov ring is created in the focus plane. The light intensity of the Cherenkov light is monitored by ADC on a spill-by-spill basis. The information concerning the Cherenkov-light intensity and shape of the ring are used to calculate the momentum distribution and divergence of the pion beam. The ratio of neutrino flux at the front detector and at Super-Kamiokande site can be expected for a neutrino energy larger than 1.0 GeV based on the decay kinematics of the pions.

A muon monitor will be installed downstream of the decay tunnel. The muon monitor is a 2 m $\times$ 2 m pad-type ionization chamber filled with He gas. The anode current induced by the muon beam is read out from the x-direction and the y-direction with an interval of 5 cm. The 2-dimensional projection of the muon intensity provides information about the beam profile. The position of the beam center is obtained with an accuracy of $\sim$2 cm.

§4. Front detector

The front detector in the KEK site is located 300 m downstream of the target. A schematic view of the front detector is shown in Figure 3. We will construct
two types of detectors. They are a 1kt water Cherenkov detector and a so-called Fine-Grained Detector.

The 1kt water Cherenkov detector is a miniature of the Super-Kamiokande detector. The detector volume of 496 tons is viewed by 860 20-inch photomultiplier tubes with a 70 cm spacing. The main purpose of the 1kt water Cherenkov detector is to compare neutrino events in the KEK site with events in the Super-Kamiokande detector using the same observation method. A direct comparison of the neutrino events cancels any systematic errors inherent to water Cherenkov detectors.

The purpose of the Fine-Grained Detector is to understand the neutrino-flux profile and energy distribution precisely at the KEK site. The Fine-Grained Detector consists of 4 detector elements: a scintillating fiber tracker, trigger counters, lead glass counters and a muon ranger.

The scintillating fiber tracker is a 20-layer “sandwich” of scintillating fiber sheets and a water target. One scintillating fiber layer consists of 4 scintillating fiber sheets (2 vertical and 2 horizontal) with a sensitive area of 2.4 m × 2.4 m. They are made of 0.7 mm φ scintillating fibers. The scintillating fiber layers are arranged with intervals of 9 cm. The water target is contained in 1.8 mm-thick aluminum tubes, and are placed between scintillation fiber layers. The scintillation light from the fibers is read by Image Intensity Tubes (IITs) and CCD cameras. From a cosmic-ray muon test, the detection efficiency of each layer was found to be better than 99%, and the position resolution of the fiber sheet was obtained to be ∼ 280 μm. The data from the scintillating fiber tracker are used to reconstruct the tracks of charged particles generated in neutrino interactions and to identify the kinematics of the neutrino interaction.

Around the scintillating fiber tracker, about 100 large plastic scintillators (∼ 4 m (length) × ∼10 cm (width) × 4 cm (thickness)) from the previous Trinstan experi-
Fig. 4. Cross-sectional view of a typical quasi-elastic scattering event in the Fine-Grained Detector obtained from a Monte-Carlo simulation

ments are aligned. The absolute time of an event is obtained by plastic scintillators with an accuracy of 0.7 nsec. This information is used to reject cosmic-ray muon background with a reduction rate of ~ 99%, and is used in the time correction of the muon chamber data. Neutrino interactions outside of the Fine-Grained Detector can also be identified by the counter.

The purpose of the lead-glass counters is to precisely measure the contamination of electron neutrinos in the muon neutrino beam. It consists of 600 lead-glass counters; each counter is 12 cm × 12 cm in acceptance. The basic idea of the electron identification is based on the response of the lead-glass counters to muons and electrons. The energy deposit of electron can be measured with a resolution of 8%/√E_e, whereas the energy deposit of muons which pass through the lead-glass counters is less than ~ 1.0GeV. Therefore, high-energy (≥ 1.2GeV) electrons can obviously be distinguished from muons. The contamination of electron neutrinos can be measured to be (1.0 ± 0.3)% when the ν_e contamination is 1%. Calibration of the lead-glass counters using cosmic-ray muons was finished in Dec. 1997.

The muon ranger consists of ~ 900 modules of drift tubes from the Venus muon chamber and 12 plates of an iron filter (10~20 cm thick). Muons generated by charged-current interactions in the water target are reconstructed with a spatial resolution of 2.2 mm. The efficiency of each drift tube layer is ~ 99%. The muon momentum is calculated from the total depth of the material (mainly iron) between the position of the neutrino interaction and the position where the muon is stopped. The muon ranger is used to obtain the muon energy with a resolution of ΔE_e/E_e = 8 ~ 10%.

A schematic view of a typical neutrino interaction in the Fine Grained detector...
Table I. Summary of the detector performance in the K2K experiment.

|                    | Fine-grained detector | 1kton detector | Super-Kamiokande |
|--------------------|-----------------------|----------------|-----------------|
| $\Delta E_\mu/E_\mu$ | $8 \sim 10\%$         | $3\%$          |                 |
| $\Delta \theta_\mu$  | $\sim 1^\circ$        | $3^\circ$      |                 |
| $\Delta V_{tid}/V_{fid}$ | $\sim 1\%$           | $\sim 10\%$   | $3\%$          |
| $\Delta E_e/E_e$     | $8%/\sqrt{E_e}$       | $3%/\sqrt{E_e}$| $3%/\sqrt{E_e}$|

Table II. Number of neutrino interactions in the fiducial volume.

|                    | Fine-grained detector | 1kton detector | Super-Kamiokande |
|--------------------|-----------------------|----------------|-----------------|
| fiducial volume    | 5.8 ton               | 21 ton         | 22500 ton        |
| (dimension)        | (2m×2m×1.1m)          | (3mφ×3m)       | (34mφ×32m)       |
| neutrino flux      | $3.0 \times 10^{12}$/cm$^2$ | $3.0 \times 10^{12}$/cm$^2$ | $2.3 \times 10^6$/cm$^2$ |
| event rate         | 0.010/spill           | 0.033/spill    | $\sim 1$/day    |
| $\nu_\mu$ event   | 171600                | 552000         | 465             |
| (quasi-elastic)    | 44200                 | 142000         | 120             |
| $\nu_e$ event     | 1250                  | 4000           | 4               |

is shown in Figure 4.

A detailed description of the Super-Kamiokande, which will be used as a far detector, has been made, and is not presented here.

The performance of the 1kt water Cherenkov detector, Fine-Grained Detector and Super-Kamiokande are summarized in Table I. Number of neutrino events expected in the fiducial volume are also shown in Table II.

§5. Sensitivity

An examination of the $\nu_e \leftrightarrow \nu_\mu$ oscillation in K2K is an appearance search. Any small contamination of $\nu_e$ in the $\nu_\mu$ beam can be confirmed by the lead-glass counter. An excellent particle-identification capability in the Super-Kamiokande detector was already examined. Therefore, a possible excess of electron neutrino events in the Super-Kamiokande detector is direct evidence of the neutrino oscillation. Although there is a possible background of $\pi^0$ from a neutral-current interaction of $\nu_\mu$, it can be easily recognized, because most of the $\pi^0$ have an energy of less than 1.0 GeV. If the oscillation parameters, $(\Delta m^2, \sin^2 2\theta) = (1 \times 10^{-2}, 1)$, are assumed, the number of electron events with $E_e > 1.5$ GeV is expected to be $\sim 90$, whereas the background from $\pi^0$ and from $\nu_e$ contamination is only $\sim 4$.

The $\nu_\mu \leftrightarrow \nu_\tau$ oscillation can be examined by studying any distortion of the neutrino energy spectrum at Super-Kamiokande. The expected neutrino energy spectrum at given neutrino oscillation parameters is shown in Figure 5. The change in the neutrino energy spectrum as well as a reduction of neutrino events would
Fig. 5. Expected $\nu_\mu$ energy spectra with Super-Kamiokande at $10^{20}$ protons on target for various $\nu_\mu \leftrightarrow \nu_\tau$ oscillation parameters (a)-(d) (data points with error bars) and for the no oscillations (solid histogram).

comprise an evidence of neutrino oscillation.

In the determination of the neutrino energy spectrum, we will employ a quasi-elastic interaction of muon neutrinos, because quasi-elastic scattering is recognized as single ring events in the Super-Kamiokande detector, and because the energy of the neutrinos can be calculated from the momentum and the scattering angle of the muon track. It should also be noted that the cross section of quasi-elastic scattering is well understood compared with that of other interactions.

The sensitivity of the $\nu_e \leftrightarrow \nu_\mu$ and $\nu_\mu \leftrightarrow \nu_\tau$ oscillation in K2K is shown in Figure 6 together with other experiments (1), (4), (11)-20) which are proposed, under construction, in data taking, or finished. The sensitive parameter regions in K2K are $\Delta m^2 \simeq 1 \times 10^{-3} \text{eV}^2$ and $\sin^2 2\theta > 0.1$ for the $\nu_e \leftrightarrow \nu_\mu$ oscillation, and $\Delta m^2 \simeq 3 \times 10^{-3} \text{eV}^2$ and $\sin^2 2\theta > 0.4$ for the $\nu_\mu \leftrightarrow \nu_\tau$ oscillation.

The first neutrino beam in K2K will be available in January, 1999.

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Fig. 6. Exclusion contours of 90% C.L. for (a)$\nu_\mu \leftrightarrow \nu_\tau$ oscillation and (b)$\nu_e \leftrightarrow \nu_\mu$ oscillation (thick solid lines). The allowed regions by Kamiokande, 1) LSND 17) and Super-Kamiokande 4) and excluded (or sensitive) regions by other experiments are also plotted. 11)- 20).

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