STATUS OF THE K2K LONG BASELINE NEUTRINO OSCILLATION EXPERIMENT

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ABSTRACT

K2K is the first long baseline accelerator experiment designed to test the region of parameter space allowed by the Super-Kamiokande atmospheric neutrino oscillation observation. It will begin taking data in March 1999.

1. Introduction

Neutrino oscillation studies have been fueled over the years by the observed anomalies both in neutrino fluxes from the Sun and from neutrinos formed in cosmic-ray interactions in the atmosphere. Measured solar ν_e fluxes are significantly lower than expectation from Standard Solar Models (SSM)[1], and observed atmospheric-neutrino fluxes have shown a ratio of muon to electron neutrinos which is substantially smaller than expectation based on the best theoretical modelling[2]. Flavor oscillations due to neutrino masses could account for these anomalies and in fact could be consistant with an assumed fermion mass hierarchy and Grand Unification theories that prefer a non-zero neutrino mass.

1.1. Results from the Super-Kamiokande detector

Until recently, interpretation of the atmospheric-neutrino data depended upon comparing the predicted ratio of muon to electron neutrino events with observations. The predicted ground-level fluxes come from semi-empirical model calculations believed to have ~25% accuracy, but cancellation of correlated errors implies that ν_μ/ν_e, the expected atmospheric-neutrino flux *ratio*, should have only ~5% uncertainty. In addition to systematic uncertainties in the model, the predicted ratio includes uncertainties in the semi-empirically calculated cross sections for neutrino interactions with oxygen nuclei in the energy region of 0.1−10 GeV.

Previous uncertainties regarding the particle identification capabilities of imaging water Čerenkov detectors for low energy charged particles were carefully studied by KEK E261A[3], a beam test experiment carried out jointly in 1994 by the Kamiokande and IMB Collaborations using a 1-kton water Čerenkov detector constructed at KEK. The beam test experiment demonstrated that the ν_μ deficit in the

atmospheric-neutrino data cannot be explained by systematic uncertainties in particle identification.

Therefore, concerns regarding the atmospheric-neutrino anomaly were primarily related to remaining detector systematic effects, unmeasured cross sections for neutrino interactions in water and calculated atmospheric-neutrino fluxes. These systematic concerns have now largly dissappeared with the recent zenith angle dependent results from Super-Kamiokande [4]. The E362 experiment (K2K)[5] will be the first accelerator experiment to probe the parameter space region pointed to by these results.

2. Description of the K2K Experiment

The E362 experimental arrangement includes a new neutrino beam line extended from the existing 12 GeV KEK Proton Synchrotron (KEK-PS) as a ν_μ source, a 1-kton water Čerenkov detector plus a fine-grained detector system within the KEK site as the "near" detector, and the existing Super-Kamiokande detector, located 250 km away from KEK, as the "far" detector. The layout of the experiment is shown in Fig.1. The experiment and the beam line have been constructed and data-taking began in March 1999.

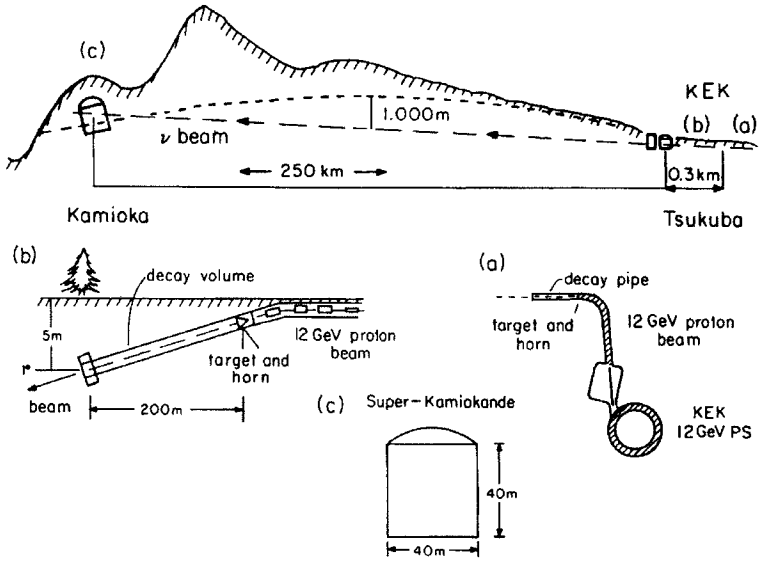

Figure 1: The overall configuration of the detectors. The front detector (b) and the Super-Kamiokande (c) are located at 300 m and 250 km from the proton target (a), respectively.

2.1. Status of the neutrino beam line

The 12 GeV proton synchrotron at KEK will produce a wide-band muon-neutrino beam with a mean energy of 1.5 GeV. The newly constructed fast extraction is intended to provide an intensity of 6×10^{12} protons on target per 1 μsec long spill every 2.2 sec. The proton beam is extracted in the EP1 area, passed along the old K6 line in the North Hall and then transported through almost a 90^o bend to the direction of Super-Kamiokande (see Fig.2).

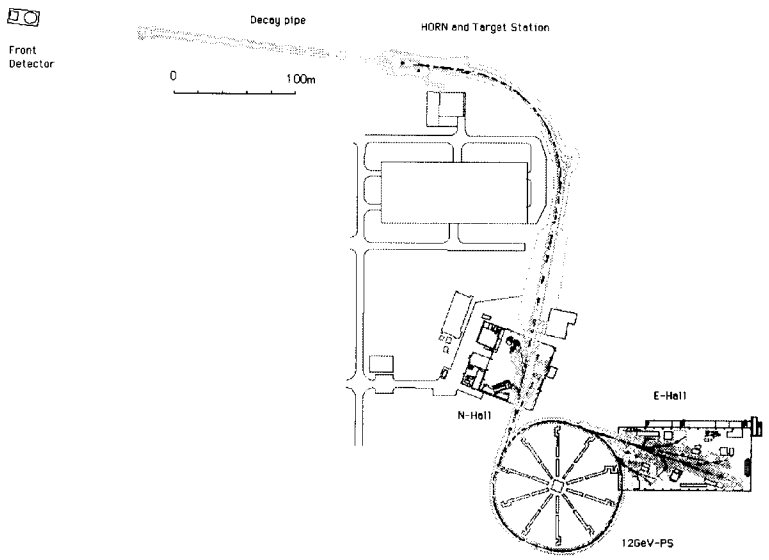

Figure 2: The Neutrino Beamline. The proton beam is extracted and then transported through almost a 90^o bend to the direction of Super-Kamiokande.

2.2. Magnetic horns

Both of the horns for focusing pions produced by the proton beam in the target have been constructed and tested with current pulses up to 250 kA of 2 msec duration. The first horn has a unique design: The target is made of aluminum, the same material that the horns are made of, and fills the front neck of the horn. It is cooled together with the inner conductor of the horn by running water. Both horns have passed rigorous structural and thermal tests under full load working conditions. They have been installed in the target hall together with the last proton beam focusing and steering magnets.

From the decay kinematics of pions produced in 12 GeV proton interactions, it is

expected that the wide-band neutrino beam produced by the two magnetic horns will be uniform to a few percent within the first few milli-radians relative to the beam axis, and thus the spectra of neutrino beams at near and far detectors will be essentially identical. Systematic corrections related to neutrino interactions in the near and far detectors will thus be minor.

2.3. Near Detector

The near detector, located 300 m from the proton beam target and 100 m from the end of the decay tunnel, consists of a 1-kton water Čerenkov detector plus a fine-grained detector with the ability to precisely observe the neutrino interaction vertex, provide tracking, and measure muon and electron energies (see Fig.3).

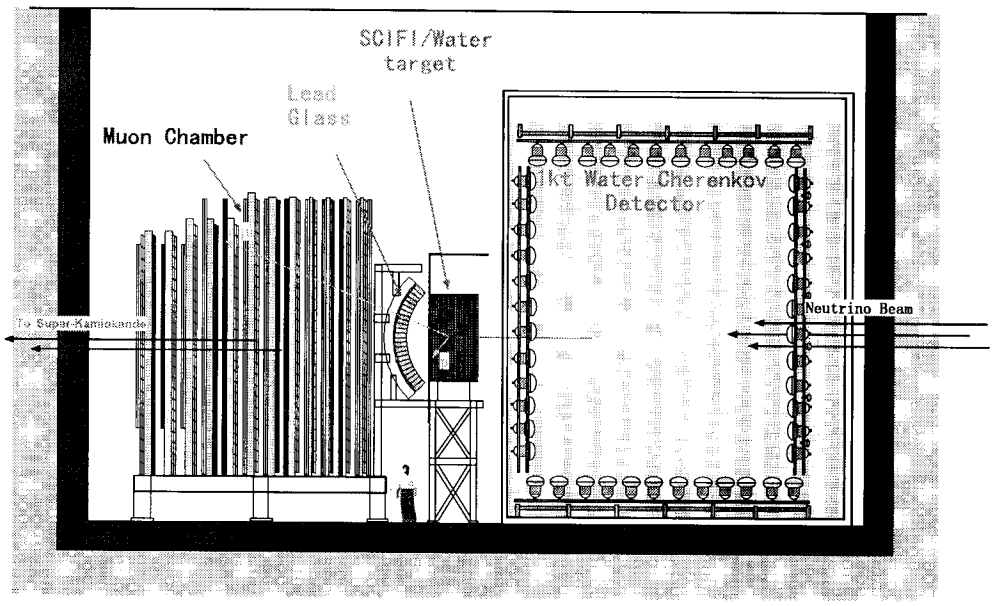

Figure 3: A schematic view of the near detector. The 1-kton cylindrical water Čerenkov detector is located in front of the fine-grained detector along the neutrino beam direction. The fine-grained detector consists of a scintillation fiber tracking device with water target, a lead-glass detector, and a muon ranger of iron plates with muon chambers along the neutrino beam direction.

The 1-kton water-Čerenkov component of the near detector is the 10 m (height)$\times$11 m (diameter) tank which was previously used in the E261A beam test experiment at KEK, with minor modifications. The fine-grained detector also uses water as target material for the neutrino beam, consisting of twenty 2.4m$\times$2.4m$\times$6cm segments totalling seven tons of water. The individual target segments are interleaved with scintillating-fiber tracking layers to provide good transverse vertex definition for neutrino interactions as well as track reconstruction capability. A lead-glass wall, used for

the TOPAZ experiment at TRISTAN and now available together with its electronics, is located behind the scintillating-fiber detector to identify electrons. A muon ranger, consisting of iron plates and drift tubes that were used for the VENUS experiment is used to measure muon energy up to 3.5 GeV with good accuracy.

In order to eliminate many systematic uncertainties, we employ water targets for all detector systems and use water Čerenkov detectors at both near and far sites. The two near-detector components will be complementary in studies of neutrino interactions in the "near" position. The water tank has its fiducial volume controlled less precisely due to poorer vertex resolution. However, unlike the fine-grained detector, the 1-kton detector can reconstruct π^0s, and due to the large size of the tank one can measure variations of the beam characteristics at larger distances from the beam axis. The fine-grained detector has a smaller target volume, but its fiducial volume is much more precisely defined due to accurate vertex measurements.

A 21-ton fiducial volume in the 1-kton detector will measure ν_e contamination and the fraction of weak neutral current (NC) events $\nu_\mu N \rightarrow \nu_\mu N' + \pi^0$, using the same methods as in the Super-Kamiokande detector. The fine-grained detector will also measure ν_e contamination.

Quasi-elastic reactions ($\nu_\mu N \rightarrow \mu^- N'$) in the fine-grained detector will serve to measure beam uniformity and the neutrino energy spectrum.

2.4. Far Detector

The far detector for E362 is the existing Super-Kamiokande underground detector, with 50 kton of pure water inside a 41 m (height)×39 m (diameter) tank. Its inner volume is viewed by 11,150 20" diameter Hamamatsu photomultiplier tubes, providing photocathode coverage equivalent to 40% of the detector surface area. The inner detector is surrounded by a 2 m thick outer layer of water viewed by 1850 8" diameter Hamamatsu tubes. The outer detector is used to veto particles coming from outside as well as providing shielding against backgrounds emanating from the surrounding rock. A nominal 22-kton fiducial volume is used to study neutrino interactions.

2.5. Control of Systematics

For a meaningful comparison of neutrino interactions at the near and far detectors, the expected fluxes and spectra of neutrinos at those distances must be well determined, *i.e.*, better than the expected effects due to neutrino oscillations. As noted above, it is expected that the KEK neutrino beam changes only by a few percent within the first few milli-radians relative to the beam axis. Thus beam pointing accuracy of 1 mrad is sufficient. A target radius of 1 m at the 300 m near-detector covers a beam segment which does not significantly differ in profile and spectrum from the beam crossing Super-Kamiokande, where the corresponding area has a radius of over

800m. The largest systematic uncertainty in extrapolating the neutrino flux to the far detector arises because the neutrinos are produced from a complex, extended source inside the decay tunnel 200 m long and 3 m in diameter. The number of neutrinos in a small unit of solid angle around the beam axis would be constant from a point source, but it decreases with distance due to the finite size of the neutrino source. The ratio of the numbers of neutrinos which intersect disks of 1 mrad acceptance at 300 m and 250 km is more than two. Therefore, accurate beam monitors along the decay tunnel will be necessary to reduce the uncertainty in the extrapolation of neutrino flux to large distances. A simulation shows that one can expect, for a spill of 6×10^{12} protons on target, an integral flux of 2×10^9 ν_μ's/m^2 at a distance of 300 m and 1.5×10^3 ν_μ's/m^2 at Super-Kamiokande.

2.5.1. Beam monitoring devices

One of the difficult problems of long baseline neutrino oscillation experiments is predicting the beam intensity and its spectrum at the position of the far detector based on the measurements made close to the end of the decay pipe. The K2K experiment uses a unique design for this purpose. In addition to the conventional primary proton beam monitoring devices and the previously mentioned muon monitor a new device is being constructed to measure the momentum and angular distribution of pions entering the decay pipe.

It consists (see Fig.4) of a vessel filled with freon of accurately controlled pressure. The pressure is chosen such that only pions, not the protons which dominate the beam at this location, produce Cherenkov light in the gas. In addition, the pressure can be regulated so that different parts of the pion spectrum can be extracted. The Cherenkov light is reflected by a mirror onto an array of photo multipliers which record the distribution of the light intensity. This distribution depends on both the pion energy spectra and their trajectories. Using the pion information (derived from the light distribution), the neutrino production from the decay pipe can be calculated with well known kinematics.

3. Sensitivity of the K2K Experiment

The expected event rates in the three detectors is shown in Table 1 for a total exposure of 10^{20} protons on target (POT).

Using these expected rates we can calculate the response of the K2K experiment to neutrino oscillations with various values of δm^2 and $sin^2 2\theta$. In Fig.5, we show the expected energy spectrum of observed single-ring ν_μ induced events in Super-Kamiokande both for the case of no oscillations and for some reasonable values of the oscillation parameters and in Fig.6 we show the sensitivity of the experiment to the oscillation parameters assuming $\nu_\mu \rightarrow \nu_\tau$ oscillations.

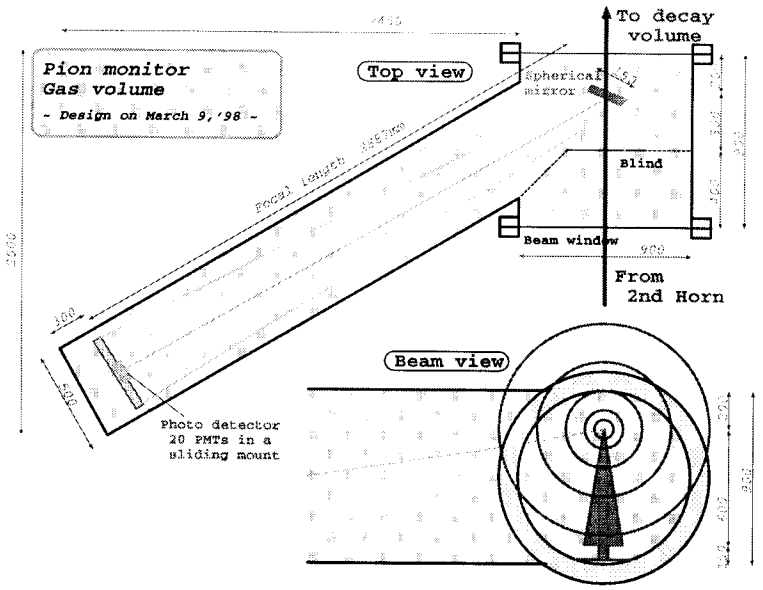

Figure 4: A Schematic of the Pion Monitor.

Table 1: Neutrino interaction rate (no oscillations) for 10^{20} protons on target.

Detector	Fine-grain	1 kt	Superk
fid. vol. (water)	4 t	21 t	22.5 kt
flux (cm^{-2})	2.6×10^{12}	2.4×10^{12}	1.8×10^{6}
ν_μ CC	63208	325526	281
quasi-elastic	21969	114216	93
single-π	18812	97283	79
multi-π	21031	106784	103
ν_μ NC	22530	116226	99
single-π^0	4642	24006	20
ν_μ total	85744	441710	381
ν_e total	884	4549	4
quasi-elastic	230	1190	1
$\bar{\nu}_\mu$ total	482	2252	2
$\bar{\nu}_e$ total	8	44	0.2

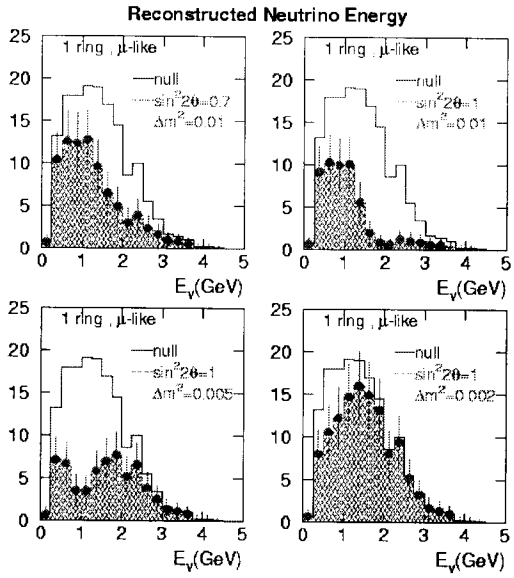

Figure 5: Expected energy spectrum of observed single-ring ν_μ induced events in Super-Kamiokande.

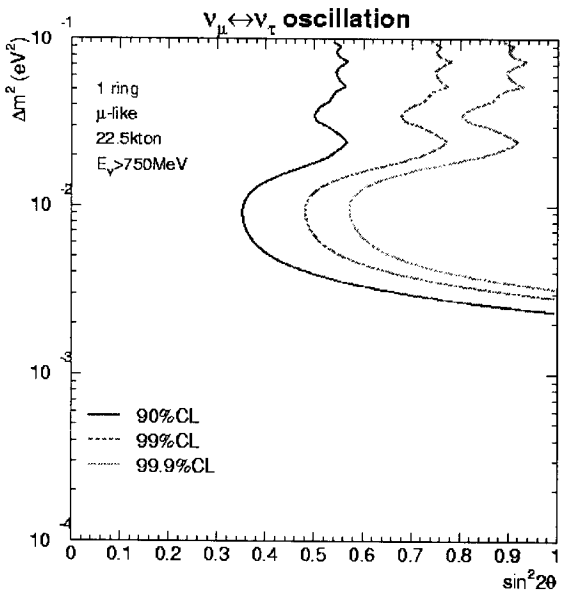

Figure 6: Sensitivity of the K2K Experiment to $\nu_\mu \rightarrow \nu_\tau$ Oscillations.

We are also sensitive to $\nu_\mu \rightarrow \nu_e$ oscillations by looking for ν_e appearance. The major background for this search is due to mis-identified π_0 events. In Fig.7, we show the energy spectrum of observed single-ring ν_e induced events in Super-Kamiokande assuming $\nu_\mu \rightarrow \nu_e$ oscillations. The background from π_0 events is also shown. In Fig.8, we show the sensitivity of the experiment to the oscillation parameters assuming $\nu_\mu \rightarrow \nu_e$ oscillations.

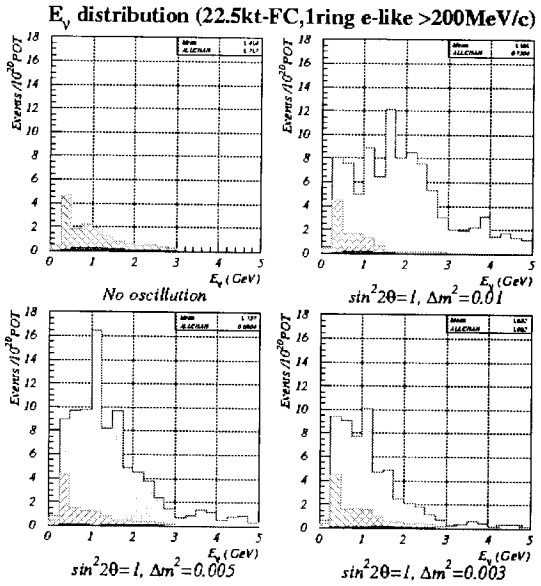

Figure 7: Expected energy spectrum of single-ring ν_e appearance events in Super-Kamiokande.

4. Conclusions

The K2K experiment is ready to begin normal data taking in March 1999. It will be the first long baseline accelerator experiment to test a large portion of the mixing region that is indicated by the atmospheric neutrino results from Super-Kamiokande. If δm^2 is larger than about 3×10^{-3} eV^2 the K2K experiment should have a definitive result.

5. References

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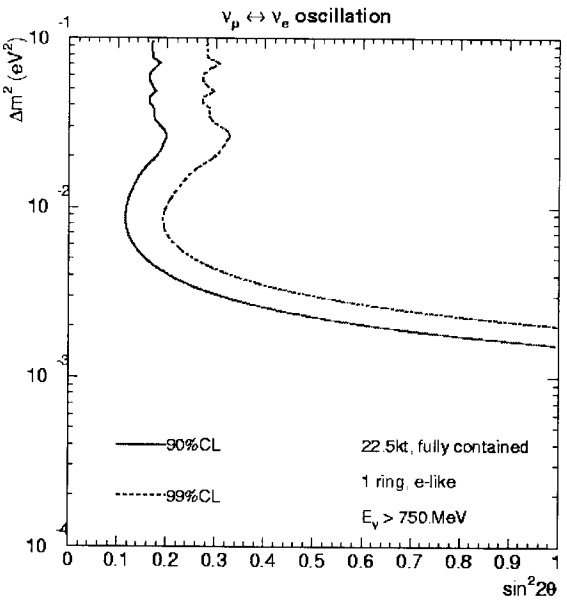

Figure 8: Sensitivity of the K2K Experiment to $\nu_\mu \rightarrow \nu_e$ Oscillations.

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