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Improved search for $\nu_\mu \to \nu_e$ oscillation in a long-baseline accelerator experiment

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We performed an improved search for $\nu_\mu \to \nu_e$ oscillation with the KEK to Kamioka (K2K) long-baseline neutrino oscillation experiment, using the full data sample of 9.2×10^{19} protons on target. No evidence for a ν_e appearance signal was found, and we set bounds on the $\nu_\mu \to \nu_e$ oscillation parameters. At $\Delta m^2 = 2.8 \times 10^{-3}$ eV^2, the best fit value of the K2K ν_μ disappearance analysis, we set an upper limit of $\sin^2 2\theta_{\mu e} < 0.13$ at 90% confidence level.

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Introduction.— We describe a search for ν_e appearance in a beam of ν_μ, which is the signature of a non-zero value of the unknown neutrino mixing parameter θ_{13}. In the current picture of neutrino oscillations, three flavors of neutrinos are related to three mass states by the Maki-Nakagawa-Sakata matrix[1]. The mixing can be described by two Δm^2 parameters ($\Delta m^2_{\rm atm}, \Delta m^2_\odot$), three mixing angles ($\theta_{23} \sim \theta_{\rm atm}$, $\theta_{12} \sim \theta_\odot$, and θ_{13}) and a CP violating phase (δ). Atmospheric ν oscillations measured by several experiments [2, 3, 4, 5] and confirmed by the beam experiment [6] are well-described by $\nu_\mu \to \nu_\tau$ oscillations with parameters $\sin^2 2\theta_{\rm atm} > 0.92$ and $1.5 \times 10^{-3} < \Delta m^2_{\rm atm} < 3.4 \times 10^{-3}$ eV^2. Solar $\nu_e \to \nu_{\mu,\tau}$ oscillations with parameters in the range $0.2 < \sin^2\theta_\odot < 0.4$ and $7 \times 10^{-5} < \Delta m^2_\odot < 9 \times 10^{-5}$ eV^2 are also consistent with multiple observations [7, 8], and are confirmed by disappearance of reactor $\bar{\nu}_e$[9]. As yet, very little is known about either θ_{13} or δ, although lack of observed disappearance of reactor $\bar{\nu}_e$ over a few km baseline[10] has shown that θ_{13} must be smaller than 12° at the $\Delta m^2_{\rm atm}$ region reported by K2K[6]. In a 2-flavor approximation, the probability of appearance of ν_e in a beam of ν_μ is given by

$$P(\nu_\mu \to \nu_e) = \sin^2 2\theta_{\mu e} \sin^2(1.27 \Delta m^2_{\mu e} L/E),$$

where L is the baseline in km, E is the neutrino energy in GeV and $\Delta m^2_{\mu e}$ is in eV^2. For the case that $\Delta m^2_{23} \sim \Delta m^2_{\rm atm} \gg \Delta m^2_{12} \sim \Delta m^2_\odot$, and $\sin^2 2\theta_{\rm atm} \sim 1$, we can take $\Delta m^2_{\mu e} \sim \Delta m^2_{\rm atm}$ and $\sin^2 2\theta_{\mu e} \sim \sin^2\theta_{23} \sin^2 2\theta_{13} \sim \frac{1}{2}\sin^2 2\theta_{13}$.

Experimental apparatus and data sample.— The KEK to Kamioka (K2K) long-baseline neutrino experiment comprises a 98% pure ν_μ beam with mean energy of 1.3 GeV, created at KEK's proton synchrotron and sent 250 km to the Super-Kamiokande (SK) detector[11]. The beam is created by colliding primary protons of 12.9 GeV/c on an aluminum target, focusing the resulting secondary pions by two electromagnetic horns, and letting pions decay in a decay pipe. The contamination of ν_e in the beam (beam ν_e) is $\sim 1\%$ at KEK site. Near neutrino detectors are employed at a 300 m baseline to measure the beam. The near detector complex includes fine-grained detectors (FGD) and a 1 kiloton water Cherenkov detector (1KT). More details of the subdetectors are found in references [12, 13, 14].

There were two running periods in K2K: K2K-I [4.8×10^{19} protons on target (POT)] corresponds to dates for which SK was instrumented with 11,146 inner detector (ID) photomultiplier tubes (PMTs). K2K-II (4.4×10^{19} POT) corresponds to dates after SK was rebuilt with 47% ID PMT density following an accident. The K2K-I period is divided into K2K-Ia (June 1999) and K2K-Ib (November 1999 to July 2001). For K2K-Ia, the horn current and target diameter were different from the subsequent phases of the experiment, and the differences of neutrino fluxes and systematic uncertainties are taken into account. For K2K-II (January 2003 to November 2004), the lead-glass calorimeter (LG) in FGD was replaced by a fully-active scintillator detector (SciBar). We have analyzed the entire K2K data sample which corresponds to 9.2×10^{19} POT in total. The statistics are almost the double of our previous published results of K2K-I [15]. The results in this paper are obtained with a revised signal selection and an improved sensitivity.

Event selection.— Our search for $\nu_\mu \to \nu_e$ signal is based on detection of charged current quasi elastic (CC-QE) interaction of ν_e in an oxygen nucleus: $\nu_e + n \to e + p$. Typically the momentum of a recoil proton from CC-QE interaction is below Cherenkov threshold in the water. Therefore only the electron, visible as a single-ring, shower-type event, is the signature of ν_e appearance.

Beam neutrino events in SK are selected based on timing information from the global positioning system (GPS) to reject cosmic-ray and atmospheric neutrino background. We start with the 112 fully-contained events in the 22.5 kiloton fiducial volume (FCFV) for K2K-I+II. The definition of the electron signal candidates is given in Ref. [15]. The signal selection begins by identifying an electron ring candidate based on the shape of Cherenkov ring pattern and opening angle. Next, signal candidates are required to have electron-equivalent energy (visible energy) above 100 MeV to remove misidentified charged pions via ν_μ-CC interactions and electrons from muon decays in which muons are below Cherenkov threshold. Finally, we require that no electron is followed by a muon decay within a 30 μsec time window.

Near the limit of θ_{13} [10] at the $\Delta m^2_{\rm atm}$ region ($\sin^2 2\theta_{\mu e} \sim 0.05$, $\Delta m^2 \sim 2.8 \times 10^{-3}$ eV^2), we obtain an oscillation probability for ν_e appearance in K2K of $\sim 10^{-2}$, which gives an expectation of a few ν_e signal events in our entire sample. Because this expected

appearance signal is so small, precise understanding of background and its reduction are crucial. One of the background sources is beam ν_e. This is responsible for 13% of background events after the selection criteria described above. The remaining 87% originate from beam ν_μ; this includes ν_μ-CC and neutral current (NC) interactions of ν_μ and ν_τ, where ν_τ appears as a result of ν_μ oscillation. This ν_μ-originated background is dominated by π^0 produced via NC interaction. A single π^0 decaying into two gamma rays can be classified by the standard atmospheric neutrino reconstruction procedure[3] as a single-ring showering event, when one gamma ray is not reconstructed, due to highly asymmetric energies or a small opening angle between the two gamma rays.

For the current analysis, we enhance the π^0 reconstruction capability with a newly introduced algorithm for electron candidate events. A second gamma-ray ring candidate is reconstructed by comparison of the observed charge and expected light patterns calculated under the assumption of two showering rings. The direction of the ring reconstructed by the standard procedure, visible energy and vertex information are used as input. We use the invariant mass of $\pi^0 \to \gamma\gamma$ (M_{inv}) from the momenta of two potential gamma-ray rings. Among single electron candidates, the π^0 background events have a value of M_{inv} close to the π^0 mass. In contrast, for a ν_e signal event, the reconstructed energy of the second fake ring tends to be small after sharing the visible energy with the two-ring configuration. Therefore M_{inv} has a dependence on the energy of the electron candidate ring(E_e).

For the final selection of candidate events, we exclude the region $M_{inv} > 100$ MeV/c^2. Then a tighter cut is applied to the events with E_e below 400 MeV, where the resolution of π^0 mass is poor and the ν_e signal shows small M_{inv}. The resultant M_{inv} vs. E_e plot is shown in Fig. 1. The signal region is optimized to maximize statistical significance assuming ($\sin^2 2\theta_{\mu e}$, Δm^2) = $(0.05, 2.8 \times 10^{-3}\mathrm{eV}^2)$. With this requirement, 70% of

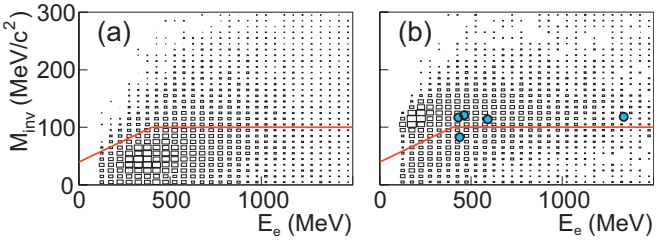

FIG. 1: Distribution of candidate events in the M_{inv}-E_e space. The selection boundary is indicated by a line with a bend for (a) signal MC events and (b) ν_μ-originated background MC events. Remaining events before the π^0 rejection in data (circles) are also shown for K2K-I and K2K-II combined. Signal MC distributions are obtained under the assumption of $\sin^2 2\theta_{\mu e} = 0.05$ and $\Delta m^2 = 2.8 \times 10^{-3}$ eV^2.

ν_μ-originated background in electron candidate events is suppressed, and the overall efficiency for selection of ν_e via CC interactions for K2K-I and K2K-II is 47% and 51%, respectively. This selection efficiency of K2K-II is a little larger than K2K-I, however, the ν_μ background expectation is also larger for K2K-II. The reduction of the data and background expectations according to the Monte Carlo (MC) simulation is summarized in Table I. After all selection cuts, we obtain one signal candidate in the data; four of five remaining before the final selection are rejected as π^0-like. (The single signal candidate of K2K-I reported in Ref. [15] is rejected by the new cuts.) This rejection capability is as expected, and a signal candidate is consistent with background expectation. A visual examination reveals the surviving candidate to be an event with more than two rings. It is consistent with a multihadron production event; these make up 14% of the background according to the MC simulation.

Background expectation.— In our MC simulation, neutrino interactions with oxygen nuclei are simulated as in Ref.[16]. The interaction models used in this analysis are the same as the $\nu_\mu \to \nu_x$ oscillation analysis [6] except that we set the cross section for CC coherent pion production to zero, based on Ref. [17].

The ν_μ energy spectrum and normalization are derived from measurements at the near detectors. The far/near ν spectrum ratio used to extrapolate near detector measurements to SK is calculated using a beam MC simulation. In the simulation, we employ the π^+ production cross-section measured by the HARP experiment[18]. This spectrum ratio is validated by in situ measurements of pions from the aluminum target[19]. With the full data set the resulting flux is consistent with the previous result[6]. The normalization of the ν_μ events is determined by the 1KT data. The expected total number of FCFV events at SK without oscillation for K2K-I and K2K-II is 81.1 and 77.4, respectively.

The number of background events is estimated to be 0.8 (0.9) for K2K-I (K2K-II); 0.6 (0.7) event is originated from ν_μ and the remaining 0.2 (0.2) is beam ν_e. The

TABLE I: Reduction of events for $\nu_\mu \to \nu_e$ search at SK. The first column lists each selection requirement. The others give, for each selection, the number of observed events, ν_μ background in the case of no oscillation, and beam ν_e, for K2K-I and K2K-II, respectively.

	K2K-I			K2K-II		
	Data	ν_μ	Beam-ν_e	Data	ν_μ	Beam-ν_e
FCFV	55	81.1	0.8	57	77.4	0.9
single ring	33	50.1	0.5	34	49.4	0.5
shower like	3	2.7	0.4	5	3.2	0.4
visible energy cut	2	2.5	0.4	5	2.9	0.4
no decay electron	1	1.9	0.3	4	2.2	0.4
non-π^0 like	0	0.6	0.2	1	0.7	0.2

background events are dominated by NC interactions and are consequently nearly insensitive to ν_μ oscillated to ν_τ; ν_τ oscillation affects the background estimation by $\sim 5\%$ at the oscillation parameters of the K2K result [6].

Systematic uncertainties.— The various contributions to the systematic uncertainty in ν_μ-originated background are summarized in Table II. Most of the error sources are related to π^0 background in NC interactions. The fraction of NC single π^0 (NC1π^0) production in the total of background events in SK is about 70%; the 1KT detector data were used for understanding its cross section in water. The 1KT measurement of the cross section ratio of NC1π^0 production to CC interaction (NC1π^0/CC) gives $0.064 \pm 0.001(stat.) \pm 0.007(sys.)$ [20], and our MC simulation predicts the ratio to be 0.065. Taking into account this measurement and the difference of the central values, we apply an uncertainty of 12% to the NC1π^0/CC ratio. For the composition of NC background other than NC1π^0, an uncertainty of 20% in the ratio of NC cross section to CC is quoted as in Ref.[21]. For coherent NC π^0 production, we account for the difference between the zero coherent pion production case and the model of Rein and Sehgal [22]. Varying these cross sections by their errors, the contributions to the expected number of events are estimated. In addition, final state interactions of nucleons and mesons inside of nuclear matter could substantially alter π^0 momenta. This effect is estimated to be 8% on the ν_μ-originated background, considering the differences in the π^0 spectrum between 1KT data and MC events.

Systematic uncertainty related to the π^0 rejection has been evaluated based on the measurement of atmospheric neutrinos in SK. For this purpose we select two data samples which include an unreconstructed gamma ray from π^0 decays in the final state. One of these is a sample of single electron events; the other is a sample of events with one muon-like and one electron-like ring reconstructed. Using both samples, an uncertainty of 19% is estimated in the M_{inv} cut in order to account for the effect of possible reconstruction biases which affect the M_{inv} distribution. Water properties also affect the π^0 reconstruction and associated errors are estimated using cosmic ray muons. The light attenuation has been measured during the entire period of operation of the SK detector. The absorption and scattering lengths were varied within their ranges accordingly, $\pm 20\%(\pm 15\%)$ for SK-I (SK-II), which results in systematic effects of $\pm 11\%$ ($\pm 6\%$) for K2K-I (K2K-II).

For the beam-ν_e contamination, the expectation is derived from the ν_e/ν_μ flux ratio at SK with the beam MC simulation and ν_μ flux extrapolation from the near detectors to SK. The beam MC expectation has been verified by measurements of ν_e/ν_μ interaction ratio at the FGD complex. The measurement by SciBar[23], covering the electron energy above 0.5 GeV, gives this ratio as $1.6 \pm 0.3(stat.) \pm 0.2(syst.)\%$. The ratio measured by LG[15] for the electron energy above 1 GeV is consistent with that of SciBar, and both show agreement with the beam MC prediction of 1.3%. The systematic uncertainty in the number of beam-ν_e background is dominated by our understanding of pion and kaon production in proton collisions on the aluminum target; ν_e contamination via muon and kaon decays is taken into account, where muons are emitted by positive pion decays. Uncertainties in the beam-ν_e background of 14% and 16% are estimated for pion and kaon production, respectively. Incorporating other possible contributions such as the single electron selection, we quote an uncertainty of $^{+32}_{-21}\%$ in total.

TABLE II: Systematic uncertainties [%] in the expectation of ν_μ-originated background. When estimating the total uncertainty, the correlations between the neutrino fluxes and the cross sections are taken into account.

	K2K-I (Ia)	K2K-I (Ib)	K2K-II
NC1π^0/CC ratio	± 8	$^{+6}_{-7}$	$^{+6}_{-7}$
NC/CC ratio (non-NC1π^0)	± 4	± 3	± 3
π^0 energy spectrum	± 8		± 8
coherent π^0 model	$^{+3}_{-10}$		$^{+3}_{-10}$
π^0 mass cut	$^{+19}_{-18}$		$^{+19}_{-17}$
water properties	± 11		± 6
neutrino flux at SK	$^{+20}_{-17}$	± 6	± 6
non-QE/QE ratio	$^{+2}_{-2}$	$^{+1}_{-1}$	$^{+1}_{-1}$
detector efficiency	± 6		± 6
single electron selection	$^{+5}_{-7}$		$^{+7}_{-8}$
total	$^{+33}_{-32}$	$^{+37}_{-26}$	$^{+39}_{-24}$

For the number of appearance signal events, the total estimated uncertainty is 15% with dominant sources coming from the ν_μ energy spectrum and the cross section ratio of CC interactions other than CC-QE (non-QE) to CC-QE measured by the near detectors.

Limits on mixing parameters.— To set an excluded parameter region in a 2-flavor oscillation model, we adopt a confidence interval construction with the Poisson distribution using the expected number of events and the observed number; these values are $1.7^{+0.6}_{-0.4}$ (in the case of no oscillation) and 1, respectively. The expected number of events $\mathcal{N}_{obs}$ can be represented by the sum of two background components and an appearance signal as

$$\mathcal{N}_{obs} = \mathcal{B}_{\nu_\mu}(\Delta m^2_{\mu e}, \sin^2 2\theta_{\mu e}) + \mathcal{B}_{beam-\nu_e} + \mathcal{S}_{\nu_e}(\Delta m^2_{\mu e}, \sin^2 2\theta_{\mu e}),$$

where $\mathcal{B}_{\nu_\mu}$ is the number of electron candidate events induced by ν_μ or oscillated to ν_τ, and $\mathcal{B}_{beam-\nu_e}$ is that of beam-ν_e. The number of $\nu_\mu \to \nu_e$ appearance signal, $\mathcal{S}_{\nu_e}$, and $\mathcal{B}_{\nu_\mu}$ depend on the probability of $\nu_\mu \to \nu_e$ oscillation. For the contribution of $\nu_\mu \to \nu_\tau$ oscillation to $\mathcal{B}_{\nu_\mu}$, we assume the best-fit parameters of the K2K ν_μ disappearance analysis[6]. In the calculation of the upper limit

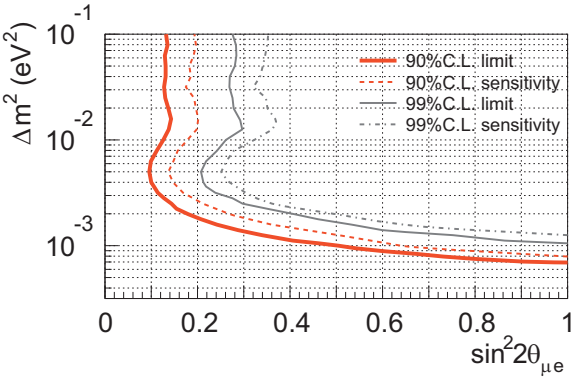

FIG. 2: The upper bound on $\nu_\mu \to \nu_e$ oscillation parameters at 90% and 99% C.L. The sensitivities of the K2K experiment for each C.L. are also indicated with dashed lines.

on $\sin^2 2\theta_{\mu e}$, the effects of systematic uncertainties are incorporated into the probability densities and the unified ordering prescription of Feldman and Cousins [24] is applied.

Figure 2 shows the upper bound on the oscillation parameters for two flavor mixing, at the 90% and 99% confidence level (C.L.). Neutrino oscillation from ν_μ to ν_e is excluded at 90% C.L. in $\sin^2 2\theta_{\mu e} > 0.13$ at $\Delta m^2_{\mu e} = 2.8 \times 10^{-3}\mathrm{eV}^2$.

Reactor $\bar{\nu_e}$ experiments provide complementary results to a search for non-zero θ_{13} with a ν_μ beam; currently the only result for ν_e appearance mode is provided by K2K. We note our resulting upper limit at 90% C.L. is $\sin^2 2\theta_{13} = 0.26$ at $\Delta m^2_{13} = 2.8 \times 10^{-3}\mathrm{eV}^2$ assuming $\sin^2 2\theta_{\mu e} = \frac{1}{2} \sin^2 2\theta_{13}$ and $\Delta m^2_{\mu e} \sim \Delta m^2_{13}$. In the same Δm^2 region, the most stringent limit from reactor experiments is $\sin^2 2\theta_{13} = 0.1$ by the CHOOZ experiment [10] and a weaker limit of 0.16 is reported by the Palo-Verde experiment [25], showing agreement with our result.

In summary, the K2K experiment finished taking data in November 2004. Starting from June 1999, we accumulated data which corresponds to 9.2×10^{19} POT. Compared to the previous search[15], we improved both the statistics and the rejection of π^0 backgrounds. As a result, we find no evidence for neutrino oscillations in the ν_e appearance mode. A single electron candidate is consistent with background expectation. We set an upper limit of $\sin^2 2\theta_{\mu e} < 0.13$ at 90% C.L. at the best-fit parameters of the ν_μ disappearance analysis.

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