First muon-neutrino disappearance study with an off-axis beam

We report a measurement of muon-neutrino disappearance in the T2K experiment. The 295-km muon-neutrino beam from Tokai to Kamioka is the first implementation of the off-axis technique in a long-baseline neutrino oscillation experiment. With data corresponding to $1.43 \times 10^{20}$ protons on target, we observe 31 fully-contained single $\mu$-like ring events in Super-Kamiokande, compared with an expectation of $104 \pm 14$ (syst) events without neutrino oscillations. The best-fit point for two-flavor $\nu_\mu \rightarrow \nu_\tau$ oscillations is $\sin^2(2\theta_{23}) = 0.98$ and $|\Delta m^2_{32}| = 2.65 \times 10^{-3}$ eV$^2$. The boundary of the 90% confidence region includes the points $(\sin^2(2\theta_{23}), |\Delta m^2_{32}|) = (1.0, 3.1 \times 10^{-3}$ eV$^2)$, $(0.84, 2.65 \times 10^{-3}$ eV$^2)$ and $(1.0, 2.2 \times 10^{-3}$ eV$^2)$.

DOI: 10.1103/PhysRevD.85.031103 PACS numbers: 14.60.Pq, 13.15.+g, 25.30.Pt, 95.55.Vj

We report a measurement of muon-neutrino disappearance in the T2K experiment. The muon-neutrino beam from Tokai to Kamioka is the first implementation of the off-axis technique [1] in a long-baseline neutrino oscillation experiment. The off-axis technique is used to provide a narrow-band neutrino energy spectrum tuned to the value of $L/E$ that maximizes the neutrino oscillation effect due to $\Delta m^2_{32}$, the mass splitting first observed in atmospheric neutrinos [2]. This narrow-band energy spectrum also provides a clean signature for subdominant electron neutrino appearance, as we have recently reported [3]. Muon-neutrino disappearance depends on the survival probability, which, in the framework of two-flavor $\nu_\mu \rightarrow \nu_\tau$ oscillations, is given by

$$P_{\text{surv}} = 1 - \sin^2(2\theta_{23}) \sin^2 \left( \frac{\Delta m^2_{32} L}{4E} \right),$$

(1)

where $E$ is the neutrino energy and $L$ is the neutrino propagation length. We have neglected subleading oscillation terms. In this paper, we describe our observation of $\nu_\mu$ disappearance, and we use the result to measure $|\Delta m^2_{32}|$ and $\sin^2(2\theta_{23})$. Previous measurements of these neutrino mixing parameters have been reported by K2K [4] and MINOS [5], which use on-axis neutrino beams, and Super-Kamiokande [6], which uses atmospheric neutrinos.
off-axis detector reconstructs exclusive final states to study neutrino interactions and beam properties corresponding to those expected at the far detector. Embedded in the refurbished UA1/NOMAD magnet (field strength 0.2 T), it consists of three large-volume time projection chambers (TPCs) [10] interleaved with two fine-grained tracking detectors (FGDs, each 1 ton). It also has a \( m^p \)-optimized detector and a surrounding electromagnetic calorimeter. The magnet yoke is instrumented as a side muon range detector.

The SK water-Cherenkov far detector [11] has a fiducial volume of 22.5 kt within its cylindrical inner detector (ID). Enclosing the ID is the 2 m-wide outer detector (OD). The front-end readout electronics [7] allow for a dead-time-free trigger. Spill timing information, synchronized by the global positioning system with <150 ns precision, is transferred from J-PARC to SK and triggers the recording of photomultiplier hits within \( \pm 500 \mu s \) of the expected neutrino arrival time.

The results presented in this paper are based on the first two physics runs: Run 1 (January–June 2010) and Run 2 (November 2010–March 2011). During this time period, the Main Ring proton beam power was continually increased and reached 145 kW with \( 9 \times 10^{13} \) protons per pulse. The fraction of protons hitting the target was monitored by the electrostatic beam position monitors, segmented secondary emission monitors and optical transition radiation monitor and found to be greater than 99% and stable in time. A total of 2, 474, 419 spills was retained for analysis after beam and far-detector quality cuts, corresponding to \( 1.43 \times 10^{20} \) protons on target (POT).

We present the study of events in the far detector with a single muonlike (\( \mu \)-like) ring. The event selection enhances \( \nu_\mu \) charged-current quasielastic interactions (CCQE). For these events, neglecting the Fermi motion, the neutrino energy \( E_\nu \) can be reconstructed as

\[
E_\nu = \frac{m_p^2 - (m_n - E_b)^2 - m_\mu^2 + 2(m_n - E_b)E_\mu}{2m_n - E_b - E_\mu + p_\mu \cos \theta_\mu}, \tag{2}
\]

where \( m_p \) is the proton mass, \( m_n \) the neutron mass, and \( E_b = 27 \) MeV is the binding energy of a nucleon inside a \(^{16}\text{O}\) nucleus. In Eq. (2), \( E_\mu \), \( p_\mu \) and \( \theta_\mu \) are, respectively, the measured muon energy, momentum and angle with respect to the incoming neutrino. The selection criteria for this analysis were fixed from Monte Carlo (MC) studies before the data were collected. The observed number of events and spectrum are compared with signal and background expectations, which are based on neutrino flux and cross-section predictions and are corrected using an inclusive measurement in the off-axis near detector.

Our predicted beam flux (Fig. 1) is based on models tuned to experimental data. The most significant constraint comes from NA61 measurements of pion production [12] in \((p, \theta)\) bins, where \( p \) is the pion momentum and \( \theta \) the polar angle with respect to the proton beam; there are 5%–10% systematic and similar statistical uncertainties in most of the measured phase space. The production of pions in the target outside the NA61-measured phase space and all kaon production are modeled using FLUKA [13,14]. The production rate of these pions is assigned systematic uncertainties of 50%, and kaon production uncertainties are estimated to be between 15% and 100% based on a comparison of FLUKA with data from Eichten et al. [15]. The software package GEANT3 [16], with GCALOR [17] for hadronic interactions, handles particle propagation through the magnetic horns, target hall, decay volume and beam dump. Additional systematic errors in the neutrino fluxes are included for uncertainties in secondary nucleon production and total hadronic inelastic cross sections, uncertainties in the proton beam direction, spatial extent and angular divergence, the horn current, and the secondary beam line component alignment uncertainties. The stability of the beam direction and neutrino rate per proton on target are monitored continuously with Interactive Neutrino GRID and are within the assigned systematic uncertainties [3].

Systematic uncertainties in the shape of the flux as a function of neutrino energy require knowledge of the correlations of the uncertainties in \((p, \theta)\) bins of hadron production. For the NA61 pion-production data [12], we assume full correlation between \((p, \theta)\) bins for each individual source of systematic uncertainty, except for particle identification where there is a known momentum-dependent correlation. Where correlations of hadron-production uncertainties are unknown, we choose correlations in kinematic variables to maximize the uncertainty in the normalization of the predicted flux.

Neutrino interactions are simulated using the NEUT event generator [18]. Uncertainties in cross sections of the exclusive neutrino processes are determined by comparisons with recent measurements from the SciBooNE.

FIG. 1. (Top) the predicted flux of \( \nu_\mu \) as a function of neutrino energy without oscillations at Super-Kamiokande and at the off-axis near detector; (bottom) the flux of \( \nu_\mu \) and \( \bar{\nu}_\mu \) at Super-Kamiokande. The shaded boxes indicate the total systematic uncertainty for each energy bin.
FIG. 2 (color online). Neutrino energy reconstructed for the CCQE hypothesis for $\nu_\mu$ CC candidates interacting in the FGD target. The data are shown using points with error bars (statistical only), and the MC predictions are in shaded histograms.


An inclusive $\nu_\mu$ charged-current (CC) measurement in the off-axis near detector (ND) is used to constrain the expected event rate at the far detector. From a data sample collected in Run 1 of $2.88 \times 10^{19}$ POT, neutrino interactions are selected in the FGDs with charged particles entering the downstream TPC. The most energetic negatively charged particle in the TPC is required to have ionization energy loss compatible with that of a muon. The analysis selects 1529 data events with 38% $\nu_\mu$ CC efficiency and 90% purity. The agreement between the reconstructed neutrino energy in data and MC is shown in Fig. 2. The ratio of measured $\nu_\mu$ CC interactions to MC is

$$R_{\text{ND}}^{\nu_\mu\text{CC}} = \frac{N_{\text{ND}}^{\text{Data,}\nu_\mu\text{CC}}}{N_{\text{ND}}^{\text{MC,}\nu_\mu\text{CC}}} = 1.036 \pm 0.028\text{(stat.)} ^{+0.044}_{-0.035}\text{(det. syst.)} \pm 0.038\text{(phys. syst.)},$$

where $N_{\text{ND}}^{\text{Data,}\nu_\mu\text{CC}}$ is the number of $\nu_\mu$ CC events, and $N_{\text{ND}}^{\text{MC,}\nu_\mu\text{CC}}$ is the MC prediction normalized by POT. The detector systematic errors in Eq. (3) are mainly due to uncertainties in tracking and particle identification efficiencies. The physics uncertainties result from cross-section uncertainties but exclude normalization uncertainties that cancel in a far/near ratio.

At the far detector, we select a $\nu_\mu$ CCQE-enriched sample. The SK event reconstruction [27] uses PMT hits in time with a neutrino spill. We select a fully contained fiducial volume sample by requiring no activity in the OD, no proactivity in the 100 $\mu$s before the event trigger time, at least 30 MeV electron-equivalent energy deposited in the ID and a reconstructed event vertex in the fiducial region. The OD veto rejects events induced by neutrino interactions outside of the ID and events where energy escapes from the ID. The visible energy requirement rejects events from radioactive decays in the detector. The fiducial vertex requirement rejects particles entering from outside the ID. Further conditions are required to enrich the sample in $\nu_\mu$ CCQE events: a single Cherenkov ring identified as a muon, with momentum $p_\mu > 200$ MeV/c, and no more than one delayed electron. The muon momentum requirement rejects charged pions and misidentified electrons from the decay of unseen muons and pions, and the delayed-electron veto rejects events with muons accompanied by unseen pions and muons. The number of events in data and MC after each selection criterion is shown in Table I. The efficiency and purity of $\nu_\mu$ CCQE events are estimated to be 72% and 61%, respectively.

We calculate the expected number of signal events in the far detector ($N_{\text{SK}}^{\exp}(E_r)$) by correcting the far-detector MC prediction with $R_{\text{ND}}^{\nu_\mu\text{CC}}$ from Eq. (3):

$$N_{\text{SK}}^{\exp}(E_r) = R_{\text{ND}}^{\nu_\mu\text{CC}} \sum_{E_t} P_{\text{surv}}(E_t) N_{\text{MC}}^{\text{SK}}(E_r, E_t).$$

In Eq. (4), $N_{\text{MC}}^{\text{SK}}(E_r, E_t)$ is the expected number of events for the no-disappearance hypothesis for T2K Runs 1 and 2 in bins of reconstructed ($E_r$) and true ($E_t$) energies. $P_{\text{surv}}(E_t)$ is the two-flavor $\nu_\mu$ survival probability and is applied to $\nu_\mu$ and $\bar{\nu}_\mu$ CC interactions but not to neutral-current interactions.

### Table I. Event reduction at the far detector.

<table>
<thead>
<tr>
<th>Selection Criterion</th>
<th>Data</th>
<th>$\nu_\mu$ CC</th>
<th>$\nu_\mu$ CC non-QE</th>
<th>$\nu_e$ CC</th>
<th>NC</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fiducial Volume interaction</td>
<td>n/a</td>
<td>24.0</td>
<td>43.7</td>
<td>3.1</td>
<td>71.0</td>
</tr>
<tr>
<td>Fully Contained Fiducial Volume</td>
<td>88</td>
<td>19.0</td>
<td>33.8</td>
<td>3.0</td>
<td>18.3</td>
</tr>
<tr>
<td>single ring</td>
<td>41</td>
<td>17.9</td>
<td>13.1</td>
<td>1.9</td>
<td>5.7</td>
</tr>
<tr>
<td>$\mu$-like</td>
<td>33</td>
<td>17.6</td>
<td>12.4</td>
<td>&lt;0.1</td>
<td>1.9</td>
</tr>
<tr>
<td>$p_\mu &gt; 200$ MeV/c</td>
<td>33</td>
<td>17.5</td>
<td>12.4</td>
<td>&lt;0.1</td>
<td>1.9</td>
</tr>
<tr>
<td>0 or 1 delayed e</td>
<td>31</td>
<td>17.3</td>
<td>9.2</td>
<td>&lt;0.1</td>
<td>1.8</td>
</tr>
</tbody>
</table>

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The sources of systematic uncertainty in \( N_{SK}^{\exp} \) are listed in Table II. Uncertainties in the near-detector and far-detector selection efficiencies are energy-independent except for the ring-counting efficiency. Uncertainty in the near-detector event rate is applied to \( N_{ND}^{\text{data}, \mu_{CC}} \) in Eq. (3). The flux normalization uncertainty is reduced because of the near-detector constraint. The uncertainty in the flux shape is propagated using the covariance matrix when calculating \( N_{SK}^{\exp} \). The near-detector constraint also leads to partial cancellation in the uncertainty in cross-section modeling, but the cancellation is not complete due to the different fluxes, different acceptances and different nuclei in the near and far detectors. The total uncertainty in \( N_{SK}^{\exp} \) is \( \pm 13.3\% \) without oscillations and \( \pm 15.0\% \) with oscillations with \( \sin^2(2\theta_{23}) = 1.0 \) and \( |\Delta m_{23}^2| = 2.4 \times 10^{-3} \) eV².

We find the best-fit values of the oscillation parameters using a binned likelihood-ratio method, in which \( \sin^2(2\theta_{23}) \) and \( |\Delta m_{23}^2| \) are varied in the input to the calculation of \( N_{SK}^{\exp} \) until

\[
2 \sum_{E_r} L_{\text{surv}} \ln \left( \frac{N_{SK}^{\text{data}}}{N_{SK}^{\exp}} \right) + (N_{SK}^{\exp} - N_{SK}^{\text{data}}) \right] \quad (5)
\]

is minimized. The sum in Eq. (5) is over 50 MeV bins of reconstructed energy of selected events in the far detector from 0–10 GeV.

Using the near-detector measurement and setting \( P_{\text{surv}} = 1.0 \) in Eq. (4), we expect a total of \( 103.6 \pm 13.8 \) (systematic) single \( \mu \)-like ring events in the far detector without disappearance, but we observe 31 events. If \( \nu_\mu \rightarrow \nu_\tau \) oscillations are assumed, the best-fit point determined using Eq. (5) is \( \sin^2(2\theta_{23}) = 0.98 \) and \( |\Delta m_{23}^2| = 2.65 \times 10^{-3} \) eV². We estimate the systematic uncertainty in the best-fit value of \( \sin^2(2\theta_{23}) \) to be \( \pm 4.7\% \) and that in \( |\Delta m_{23}^2| \) to be \( \pm 4.5\% \). The reconstructed energy spectrum of the 31 data events is shown in Fig. 3 along with the expected far-detector spectra without disappearance and with best-fit oscillations.

We construct confidence regions in the oscillation parameters using the method of Feldman and Cousins [28]. Statistical variations are taken into account by Poisson fluctuations of toy MC data sets, and systematic uncertainties are incorporated using the method of Cousins and Highland [29,30]. The 90% confidence region for \( \sin^2(2\theta_{23}) \) and \( |\Delta m_{23}^2| \) is shown in Fig. 4 for combined statistical and systematic uncertainties.

We also carried out an alternate analysis with a maximum likelihood method. The likelihood is defined as:

\[
L = L_{\text{norm}}(\sin^2(2\theta_{23}), \Delta m_{32}^2, f) \times L_{\text{shape}}(\sin^2(2\theta_{23}), \Delta m_{32}^2, f)L_{\text{sys}}(f), \quad (6)
\]
where the first term is the Poisson probability for the observed number of events, and the second term is the unbinned likelihood for the reconstructed neutrino energy spectrum. The vector $\mathbf{f}$ represents parameters related to systematic uncertainties that have been allowed to vary in the fit to maximize the likelihood, and the last term in Eq. (6) is a multidimensional Gaussian probability for the systematic error parameters. The result is consistent with the analysis described earlier. The best-fit point for this alternate analysis is $\sin^2(2\theta_{23}) = 0.99$ and $|\Delta m^2_{32}| = 2.63 \times 10^{-3}$ eV$^2$. The 90% confidence region for the neutrino oscillation parameters is shown in Fig. 4.

In conclusion, we have reported the first observation of $\nu_\mu$ disappearance using detectors positioned off-axis in the beam of a long-baseline neutrino experiment. The values of the oscillation parameters $\sin^2(2\theta_{23})$ and $|\Delta m^2_{32}|$ obtained are consistent with those reported by MINOS [5] and Super-Kamiokande [6,31].

We thank the J-PARC accelerator team for the superb accelerator performance and CERN NA61 colleagues for providing essential particle production data and for their fruitful collaboration. We acknowledge the support of MEXT, Japan; NSERC, NRC and CFI, Canada; CEA and CNRS/IN2P3, France; DFG, Germany; INFN, Italy; Ministry of Science and Higher Education, Poland; RAS, RFBR and the Ministry of Education and Science of the Russian Federation; MEST and NRF, South Korea; MICINN and CPAN, Spain; SNSF and SER, Switzerland; STFC, U.K.; NSF and DOE, USA. We also thank CERN for their donation of the UA1/NOMAD magnet and DESY for the HERA-B magnet mover system. In addition, participation of individual researchers and institutions in T2K has been further supported by funds from: ERC (FP7), EU; JSPS, Japan; Royal Society, UK; DOE Early Career program, and the A.P. Sloan Foundation, USA.