Search for Electron Antineutrino Appearance in a Long-baseline Muon Antineutrino Beam


(The T2K Collaboration)

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Electron antineutrino appearance is measured by the T2K experiment in an accelerator-produced antineutrino beam, using additional antineutrino beam operation to constrain parameters of the PMNS mixing matrix. T2K observes 15 candidate electron antineutrino events with a background expectation of 9.3 events. Including information from the kinematic distribution of observed events, the hypothesis of no electron antineutrino appearance is disfavored with a significance of 2.4σ and no discrepancy between data and PMNS predictions is found. A complementary analysis that introduces an additional free parameter which allows non-PMNS values of electron neutrino and antineutrino appearance also finds no discrepancy between data and PMNS predictions.

Introduction—The observation of neutrino oscillations has established that each neutrino flavor state (e, μ, τ) is a superposition of at least three mass eigenstates (m₁, m₂, m₃) [1–4]. The phenomenon of oscillation is modeled by a three-generation flavor-mass mixing matrix, called the Pontecorvo-Maki-Nakagawa-Sakata (PMNS) matrix [5, 6]. With the discovery of non-zero θ₁₃ and the explicit observation of ν₂ → ν₃ appearance oscillation [7], it is now crucial to test the PMNS framework and establish if it is sufficient to explain all neutrino and antineutrino oscillation observations. One such test is to search for the CP-reversed appearance oscillation of νₑ to νₑ. A search for this process in the Tokai-to-Kamioka (T2K) experiment was reported in reference [8], and recent results from the NOvA experiment show a significance of 4.4σ [9]. In this Letter, we report a search for electron antineutrino appearance at the T2K experiment with an improved event selecton and a dataset more than a factor of two larger than previous T2K results.

The T2K Experiment—The T2K experiment [10] begins with a 30 GeV proton beam from the J-PARC main ring striking a graphite target, producing pions and kaons. These charged hadrons are focused by a system of three magnetic horns to decay in a 96 m decay volume. Positively charged hadrons are focused to produce a beam of predominantly neutrinos (“neutrino mode”); negatively charged hadrons are focused for a beam of predominantly antineutrinos (“antineutrino mode”).

An unmagnetized on-axis near detector (INGRID) and a magnetized off-axis (2.5°) near detector (ND280) sample the unoscillated neutrino beam 280 m downstream from the target station and monitor the beam direction, composition, and intensity and constrain neutrino interaction properties. The unmagnetized Super-Kamiokande (SK) 50 kt water-Cherenkov detector is the T2K far detector, and samples the oscillated neutrino beam 2.5° off axis and 295 km from the production point.

The analysis presented here uses data collected from January 2010 to June 2018. The data set has an exposure of 1.63 × 10²¹ protons on target (POT) in antineutrino mode, with an additional data set of 1.49 × 10²¹ POT in neutrino mode used to constrain PMNS oscillation parameters acting as systematic uncertainties in the analysis. The ND280 detector uses an exposure of 0.58 × 10²¹ POT in neutrino mode and 0.39 × 10²¹ POT in antineutrino mode.

Analysis Strategy—The significance of νₑ appearance is evaluated by introducing the parameter β, which multiplies the PMNS oscillation probability P(νₑ → νₑ):

\[ P(νₑ → νₑ) = β \times P_{\text{PMNS}}(νₑ → νₑ) \]  \hspace{1cm} (1)

The analysis is performed allowing both β = 0 and β = 1 to be the null hypothesis, where both hypotheses fully account for uncertainties in the values of the oscillation and systematic parameters. Two analyses are performed on each hypothesis to obtain corresponding p-values: one uses only the number of events (rate-only); while the other also uses information from the kinematic variables of events (rate+shape).

The total number of candidate νₑ events in the antineutrino beam mode is used as the test statistic to calculate the rate-only p-value. The test statistic

\[ Δχ^2 = χ^2(β = 0) - χ^2(β = 1) \]  \hspace{1cm} (2)

is used to calculate the rate+shape p-value, where the \( χ² \) values are calculated by marginalizing over all systematic and oscillation parameters, including the mass ordering.

In both analyses, other data samples—ν₁ν-like and ν₁τ-like in neutrino beam mode and νₑ-like in antineutrino beam
A complementary analysis allows $\beta$ to be a continuous free parameter with limits between 0 and infinity. In this analysis only, in addition to $\beta$ multiplying $P_{PMNS}(\bar{\nu}_\mu \rightarrow \nu_e)$ as in Eq. 1, the probability $P_{PMNS}(\nu_\mu \rightarrow \nu_e)$ is multiplied by a factor $1/\beta$. This formulation—slightly different from above—was chosen for its property of anti-correlation in shifting probability between neutrinos and antineutrinos. The extra degree of freedom allows the fit to explore areas away from the PMNS constraint to more accurately reflect the information given by the data. Credible interval contours in the $P(\nu_\mu \rightarrow \nu_e)$ and $P(\bar{\nu}_\mu \rightarrow \bar{\nu}_e)$ parameter space, the main result of the analysis, are then compared against T2K data fit with $\beta$ fixed to 1 to test the compatibility between the T2K data and the PMNS model constraining the standard fit.

**Neutrino Beam Flux**—The primary signal data sets were taken in antineutrino mode. The flux was predicted by a Monte Carlo (MC) simulation incorporating the FLUKA2011 interaction model [12] tuned to the results of recent external hadron production experiments including the NA61/SHINE experiment at CERN [13–15]. The INGRID detector is used to monitor the beam axis direction and total flux stability.

The resultant flux model [16–18] estimates unoscillated neutrino and antineutrino fluxes at all detectors as well as their uncertainties and correlations. The flux at ND280 and SK peaks at 600 MeV, where 96.2% of the beam is composed of $\bar{\nu}_\mu$ and 0.46% $\nu_e$. The remainder of the beam is almost entirely $\nu_\mu$. This wrong sign contamination is greater in antineutrino mode than neutrino mode.

**Neutrino Interaction Model**—The NEUT (v5.3.3) neutrino interaction generator [19] is used to generate simulated neutrino events. The model used is described in references [8] and [11]. The most relevant contributions for this analysis are highlighted here.

The dominant neutrino-nucleus interaction topology near 600 MeV, charged current quasielastic (CCQE)-like, is defined as an interaction with one charged lepton and zero pions in the final state. The nucleus is modeled with a relativistic Fermi gas (RFG) modified by a random phase approximation (RPA) to account for long-range correlations [20]. A multinucleon component is included with the Nieves 2p-2h model [21, 22], which contains both meson exchange current ($\Delta$-like) and correlated nucleon pair (non-$\Delta$-like) contributions. Parameters representing systematic uncertainties for the CCQE-like mode include the nucleon axial mass, $M_A^{QE}$; the Fermi momentum for $^{12}$C and $^{16}$O; the 2p-2h normalization term for $\nu$ and $\bar{\nu}$ separately; four parameters controlling the RPA shape as a function of $Q^2$, and the relative contributions of the $\Delta$-like and non-$\Delta$-like contributions to 2p-2h in $^{12}$C and $^{16}$O. The RPA parameters have Gaussian priors to cover the theoretical shape uncertainty given in [23, 24], and the 2p-2h shape contribution has a 30% correlation between $^{12}$C and $^{16}$O; all other priors are uniform. Other neutrino-nucleus processes are subdominant, and their rates are constrained via appropriate uncertainties.

Differences between muon- and electron-neutrino interactions are largest at low energies and occur because of final-state lepton mass and radiative corrections. A 2% uncorrelated uncertainty is added for each of the electron neutrino and antineutrino cross sections relative to those of muons and another 2% uncertainty anticorrelated between the two ratios [25].

Some systematic uncertainties are not easily included by varying model parameters. These are the subjects of “simulated data” studies, where simulated data generated from a variant model are analyzed under the assumptions of the default model. The model variations that produce the largest changes in the $\tau_\beta$ far detector spectra are an alternate single resonant pion model [26], and ad-hoc models driven by observed discrepancies in the near detector kinematic spectra, where the discrepancy is modeled as having either 1p-1h, 2p-2h-$\Delta$-like, and 2p-2h-non-$\Delta$-like kinematics. None of the variant models studied showed differences in the sensitivity values at greater than the 0.1σ level.

**Near Detector Data Constraints**—The ND280 detector is used to fit unoscillated samples of charged current (CC) muon neutrino interaction events to constrain flux and cross section systematic uncertainties for the signal and background models of SK events. The samples—unchanged from reference [11]—are selected from events that begin in one of two fine-grained detectors (FGDs) and produce tracks that enter the time-projection chambers (TPCs), which are interleaved with the FGDs. Both FGDs are composed of layers of bars of plastic scintillator, and the more downstream FGD additionally has panels of water interleaved between layers of scintillator.

In neutrino beam mode, in each FGD, the CC events (defined as containing negatively charged muon-like track) are split into three subsamples: a CC0 sample, with zero pions in the final state, enhanced in CCQE-like interactions; a CC1$\pi^+$ sample, with one $\pi^+$ in the final state, enhanced in resonant pion interactions; and a CC Other sample, containing all other CC events. In antineutrino beam mode, in each FGD, there are selected interactions with positively charged muons (($\bar{\nu}$)-like) and negatively charged muons (($\nu$)-like). The latter constrains the wrong-sign contamination, which is larger in antineutrino beam mode. Each of these selections is divided into two topologies: containing a single track and containing multiple tracks.

All samples are fit simultaneously and are binned in lepton momentum, $p_\nu$, and lepton angle, $\cos \theta_\mu$, relative to the average beam neutrino direction. A binned likelihood fit to the data is performed assuming a Poisson-distributed number of events in each bin with an expectation computed from the flux, cross section, and ND280 detector models. The fit returns central values and correlated uncertainties for systematic uncertainty parameters that are constrained by the near detector, marginalizing over near detector flux and detector systematic parame-
the total expected background is 9.3 events including 3.0
rameters above, a signal yield of 7.4 events is expected,
intrinsic
ecentration and the ring is identified as electron-like; 4) the dis-
struction cuts have an efficiency of 71.5%
for \( \bar{\nu}_e \) events that satisfy the fully-contained and fiduc-
cial requirements. The new event selection increases the
yield of \( \bar{\nu}_e \) signal by approximately 20% compared to
the previous analysis, primarily due to the new fiducial
cuts, with no loss of purity. Assuming oscillation pa-
parameter values near the best fit of previous T2K anal-
yses of \( \sin^2 \theta_{23} = 0.528, \sin^2 \theta_{13} = 0.0212, \sin^2 \theta_{12} =
0.304, \Delta m^2_{23} = 2.509 \times 10^{-3} \text{eV}^2/c^4, \Delta m^2_{12} = 7.53 \times
10^{-5} \text{eV}^2/c^4, \delta_{CP} = -1.601, \) normal ordering and \( \beta = 1, \)
the total expected background is 9.3 events including 3.0
\( \nu_e \) interactions resulting from oscillations of \( \nu_e \) in the
beam. The remaining major sources of background are
intrinsic \( \nu_e \) and \( \bar{\nu}_e \) in the beam (4.2 events) and neutral-
current interactions (2.1 events). With the oscillation pa-
parameters above, a signal yield of 7.4 events is expected,
for a total prediction of 16.8 events.

Fig. 1 shows the fifteen observed data events superim-
posed on a prediction generated using the above oscilla-
tion parameter values.

**Results**—The \( \bar{\nu}_e \) appearance \( p \)-values are cal-
culated by considering the rate-only and rate+shape test
statistics of an ensemble of 2 \( \times \) 10^4 pseudo-experiments.
Each pseudo-experiment is generated by randomizing
systematic parameters—including oscillation parameters—
and applying statistical fluctuations. Four control sam-
plies, \( \nu \) mode single-ring e-like and \( \bar{\nu}_e \) CC1\( \pi \)-like (single-
ring e-like accompanied by electron decay) and both
\( \nu \) and \( \bar{\nu}_e \) mode single-ring \( \mu \)-like, are used to constrain
the distribution of oscillation parameters of the pseudo-
experiments. The four control samples of many pseudo-
experiments are compared to data, and rejection sam-
ping is used to select 2 \( \times \) 10^4 that are most probable,
according to data. The systematic parameters are then
marginalized over using a numeric integration technique
(2 \( \times \) 10^5 samples of the systematic parameter space)
when calculating the rate+shape test statistic. Both the
number of pseudo-experiments and the number of points
used for the numerical integration were studied and se-
lected to ensure \( p \)-value stability.

When producing the pseudo-experiments and
marginalizing over systematic uncertainties, Gauss-
ian prior probabilities on the following oscillation
parameters are used: \( \sin^2 2\theta_{12} = 0.846 \pm 0.021; \)
\( \Delta m^2_{21} = (7.53 \pm 0.18) \times 10^{-5} \text{eV}^2/c^4; \) and \( \sin^2 2\theta_{13}
(0.0830 \pm 0.0031) \) [28]. The mass ordering is randomized
with a probability of 0.5 for NO, 0.5 for IO. The
other PMNS parameters are randomized using uniform
prior probabilities with limits set based on previous
experiments. Systematic parameters are randomized
according to the constraints set by the near detector fit.

When predicted distributions are compared to data,
a binned Poisson likelihood is used for all five SK data
samples. The \( \nu \)-like samples use a 2D distribution in
the reconstructed neutrino energy, \( E_{\text{rec}} \), and the recon-
structed neutrino angle with respect to the average beam
direction, \( \theta \). The \( \mu \)-like samples use a 1D distribution in
the reconstructed neutrino energy.

For the rate+shape analysis, the likelihood for a
pseudo-experiment is defined as the product of the like-
lihoods of the \( \nu \) mode single-ring e-like sample, \( \lambda_{\nu_e} \), and
the control samples, \( \lambda_c \). The test statistic is then calcu-
lated as in equation (3), by averaging this likelihood over
FIG. 1. Predicted \( \bar{\nu} \) mode single-ring e-like spectrum
(coloured histogram) compared against T2K data (white/blue
points). The distribution is a function of both the recon-
structed neutrino energy and the reconstructed angle between
the outgoing lepton and the neutrino direction.
samples of the systematic parameter space, $a_i$. When the
generated distribution of the test statistic is calculated,
$\lambda_{\nu_e}$ is compared to the pseudo-experiment data, $E$, and
$\lambda_e$ is compared to data, $D$; when the test statistic for the
real data is calculated, both likelihoods are compared to
data.

\[
\chi^2(\beta) = -2 \ln \left[ \frac{1}{N} \sum_{i=1}^{N} \lambda_{\nu_e}(\beta, a_i; E) \cdot \lambda_e(\beta, a_i; D) \right]
\]

An independent, complementary analysis uses the
kinematic variable of outgoing lepton momentum, $p_l$ in-
stead of reconstructed neutrino energy, and additionally
uses weighting of pseudo-experiments instead of rejection
sampling. Both analyses were found to give consistent
test statistic distributions and therefore $p$-values.

The distributions of the rate-only and rate+shape test
statistics for the $\beta = 0$ and $\beta = 1$ hypotheses are shown
in Fig. 2. These distributions are integrated from the
data test statistic to obtain right(left)-tailed $p$-values for
the $\beta = 0(1)$ hypothesis. The observed number of events
in the $\bar{\nu}$ mode single-ring $e$-like sample in SK was 15,
compared to a prediction of 16.8. The observed data
$\Delta\chi^2$ value in the rate+shape analysis was 3.811 and the
prediction was 6.3. The resulting $p$-values are shown in
Tab. 1. Both the rate-only and rate+shape analyses
disfavor the no-$\nu_e$-appearance hypothesis ($\beta = 0$) more
than the PMNS $\nu_e$-appearance hypothesis ($\beta = 1$). Com-
pared to the prediction, a slightly weaker exclusion of the
no $\nu_e$ appearance hypothesis ($\beta = 0$) is observed due to
observing fewer events than expected. The rate+shape
analysis gives a stronger observed exclusion of both hy-
opthoses than the rate-only analysis, due to the extra
shape information used to discredit each hypothesis.

![Fig. 2. Test statistic distributions taken from the $\beta = 0$ and $\beta = 1$ pseudo-experiment ensembles for the rate-only analysis (left) and rate+shape analysis (right). Here $N_{\text{events}}$ denotes the number of observed events in the $\bar{\nu}$ mode single-ring $e$-like sample.](image)

### Table 1. $p$-values and significance of the $\beta = 0$ and $\beta = 1$ hypotheses using both the rate-only and rate+shape analyses

<table>
<thead>
<tr>
<th>$\beta$ Analysis</th>
<th>Expected</th>
<th>Observed</th>
<th>Expected</th>
<th>Observed</th>
</tr>
</thead>
<tbody>
<tr>
<td>rate-only</td>
<td>0.019</td>
<td>0.059</td>
<td>2.36</td>
<td>1.89</td>
</tr>
<tr>
<td>rate+shape</td>
<td>0.006</td>
<td>0.016</td>
<td>2.76</td>
<td>2.40</td>
</tr>
<tr>
<td>rate-only</td>
<td>0.379</td>
<td>0.321</td>
<td>0.88</td>
<td>0.99</td>
</tr>
<tr>
<td>rate+shape</td>
<td>0.409</td>
<td>0.300</td>
<td>0.83</td>
<td>1.04</td>
</tr>
</tbody>
</table>

Continuous $\beta$—A complementary analysis allows $\beta$ to
be a free parameter, which allows for a continuum of non-
PMNS models, rather than only the single $\beta = 0$ no-$\nu_e$-
appearance case. The impact of this analysis is shown
in the parameter space of $P(\nu_\mu \to \nu_e) \sim P(\bar{\nu}_\mu \to \bar{\nu}_e)$,
and in the $\nu_e$ vs $\bar{\nu}_e$ event rate space. Varying $\delta_{CP}$ at a
fixed energy creates an ellipse with a negatively sloping
major axis in the biprobability phase space. Switching
the mass ordering shifts the center of the ellipse along the
$P(\nu_\mu \to \nu_e) = -P(\bar{\nu}_\mu \to \bar{\nu}_e)$ axis. Other oscillation
parameters shift the ellipses along the identity line in the
biprobability space. Two ellipses are shown on the
left pane in Fig. 3 in orange and brown, with the input
oscillation parameter values taken from the $\beta = 1$ fit;
the eccentricity of the ellipses is very large for the T2K
experiment, which makes them appear like lines. In the
eellipses, the bottom right corresponds to $\delta_{CP} = -\pi/2$,
top left to $\delta_{CP} = e^{i\pi/2}$, and the middle to $\delta_{CP} = 0, \pm \pi$.

Credible interval contours (68% and 90%) are pro-
duced by a Bayesian Markov Chain Monte Carlo
(MCMC) for the standard, fixed $\beta = 1$ parameter-
tization and the new non-PMNS continuous-$\beta$ parameteri-
tization. These are shown in Fig 3 on the biprobability
space (left panel) and the bievent space (right panel). In
the biprobability plot, both the credible intervals and the
expectation ellipses are calculated with neutrino energy
fixed to 600 MeV.

In the biprobability fit with $\beta$ fixed to 1, two lobes
appear in the contours, which correspond to the two mass
orderings: the upper lobe to the inverted orderings, and
the lower to the normal ordering. These lobes coincide
with the maximally $CP$-violating $\delta_{CP}$ value regions of
the two T2K expectation ovals, shown in brown (normal
order) and orange (inverse ordering). The width of the
credible intervals comes mainly from the uncertainties in
$\sin^2(2\theta_{13})$ and $\sin^2(\theta_{23})$, and height from $\delta_{CP}$ and the
mass ordering. This effect disappears in the bievent space
after including statistical fluctuations in the contours for
easier comparison against the data point.

The free $\beta$ fit explores a larger area, especially in
$P(\bar{\nu}_\mu \to \bar{\nu}_e)$ and $\nu_e$, which is expected; the lower num-
ber of $\bar{\nu}_e$ than $\nu_e$ candidate events leads to a higher
uncertainty in $P(\bar{\nu}_\mu \to \bar{\nu}_e)$, when not constrained by
the PMNS model; additionally, the two probabilities are
now decoupled due to the additional $\beta$ parameter, giving
an independent results for both probabilities and both
event rates. These credible intervals can be used to com-
pare other neutrino oscillation models against the fit con-
Conclusions—The T2K collaboration has searched for \( \bar{\nu}_e \) appearance in a \( \bar{\nu}_\mu \) beam using a data set twice as large as in its previous searches. The data have been analyzed within two frameworks, and have been compared to predictions with either no \( \tau_e \) appearance or \( \tau_\mu \) appearance as expected from the PMNS model prediction. In both frameworks, the data are consistent with the presence of \( \bar{\nu}_e \) appearance and no significant deviation from the PMNS prediction is seen. Using full rate and shape information, the no-appearance scenario is disfavored with a significance of 2.40 standard deviations.

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FIG. 3. Biprobability (left) and bievent (right) credible interval comparison between the standard fit constrained by the PMNS (light blue) model and the non-PMNS fit with the free \( \beta \) parameterization (dark blue). The maximum posterior density point is marked as the 2D mode. The narrow T2K prediction oval for normal and inverse mass orderings are in brown and orange respectively. In the ellipses, the bottom right corresponds to \( \delta CP = -\pi/2 \), top left to \( \delta CP = \pi/2 \), and the middle to \( CP = 0, \pm \pi \). All probabilities are calculated at 600 MeV. The 90% and the 68% credible intervals from both fitting methods are well within the 68% CI in both fits after including the statistical fluctuations.

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