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

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Electron antineutrino appearance is measured by the T2K experiment in an accelerator-produced antineutrino beam, using additional neutrino beam operation to constrain parameters of the Pontecorvo-Maki-Nakagawa-Sakata (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 2.40σ 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.

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account for uncertainties in the values of the oscillation and systematic parameters. The $\beta = 0$ case determines if $\bar{\nu}_e$ events can be seen above background in the experiment, and the $\beta = 1$ case determines if the data is consistent with PMNS. 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 $\bar{\nu}_e$ events in the antineutrino beam mode is used as the test statistic to calculate the rate-only $p$ value. The test statistic

$$\Delta \chi^2 = \chi^2(\beta = 0) - \chi^2(\beta = 1)$$

is used to calculate the rate + shape $p$ value, where the $\chi^2$ values are calculated by marginalizing over all systematic and oscillation parameters, including the mass ordering. In both analyses, other data samples—$\nu_\mu$-like and $\nu_e$-like in neutrino beam mode and $\bar{\nu}_e$-like in antineutrino beam mode—are used to constrain other PMNS oscillation parameters, as in other T2K analyses [11].

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 $P_{\text{PMNS}}(\bar{\nu}_e \rightarrow \nu_e)$ as in Eq. (1), the probability $P_{\text{PMNS}}(\nu_\mu \rightarrow \nu_e)$ is multiplied by a factor $1/\beta$. This formulation—slightly different from above—was chosen for its property of anticorrelation 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 datasets 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% $\bar{\nu}_e$. 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 Refs. [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 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, $M_A^{Q^2}$, 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 $\nu_e$ 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 $p - 1h$, $2p - 2h - \Delta$-like, and $2p$-$2h$-non-$\Delta$-like kinematics. None of the variant models studied showed differences in the sensitivity values at greater than the 0.1$\sigma$ 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 Ref. [11]—are selected from events that begin in one of two fine-grained detectors (FGDs) and produce tracks that enter the time-projection chambers, 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 muonlike track)
are split into three subsamples: a CC0π sample, with zero pions in the final state, enhanced in CCQE-like interactions; a CC1π± sample, with one π± 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 (νe-like) and negatively charged muons (νμ-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, \( p_\mu \), 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 parameters. Some uncertainties on neutral current and νe events cannot be constrained by these ND280 samples and those parameters are passed to the appearance analysis with their original prior.

The MC prediction before fitting underestimates the data by 10%–15%, consistent with previous T2K analyses. The agreement between the MC prediction after fitting and data is good, with a \( p \) value of 0.473. The fit to the ND280 data reduces the flux and the ND280-constrained interaction model uncertainties on the predicted electron antineutrino sample event rate at the far detector from 14.6% to 7.6%.

\( \bar{\nu}_e \) SK selection.—Unlike in the previous analysis, SK events are reconstructed and selected using the new reconstruction algorithm described in Ref. [27]. A \( \bar{\nu}_e \) event candidate in SK must meet the following criteria: (i) it is within the beam time window as determined from a GPS time stamp, and its Cherenkov light is fully contained in the SK inner detector, with minimal outer-detector activity; (ii) the reconstructed vertex is at least 80 cm from the inner-detector wall; (iii) only one Cherenkov ring candidate is found in the reconstruction and the ring is identified as electronlike; (iv) the distance from the vertex to the detector wall is greater than 170 cm along the track direction; (v) the visible energy in the event is greater than 100 MeV; (vi) there is no evidence of delayed activity consistent with a stopped muon decay; (vii) the reconstructed energy under a quasielastic scattering hypothesis is less than 1250 MeV; (viii) the ring is inconsistent with a π0 decay hypothesis.

These reconstruction cuts have an efficiency of 71.5% for \( \bar{\nu}_e \) events that satisfy the fully contained and fiducial 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 parameter values near the best fit of previous T2K analyses of
used: \( \sin^2 2\theta_{12} = (0.846 \pm 0.021) \), \( \Delta m^2_{21} = (7.53 \pm 0.18) \times 10^{-5} \text{ eV}^2/\text{c}^4 \), 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 and 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 \( \nu_e \)-like samples use a 2D distribution in the reconstructed neutrino energy, \( E_{\text{rec}} \), and the reconstructed 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 pseudoexperiment is defined as the product of the likelihoods of the \( \nu_e \) mode single-ring \( e \)-like sample, \( \lambda_{\nu_e} \), and the control samples, \( \lambda_c \). The test statistic is then calculated as in Eq. (3), by averaging this likelihood over samples of the systematic parameter space, \( a_i \). When the generated distribution of the test statistic is calculated, \( \lambda_e \) is compared to the pseudoexperiment data, \( E \), and \( \lambda_c \) is compared to data, \( D \); when the test statistic for the real data is calculated, both likelihoods are compared to data,

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

An independent, complementary analysis uses the kinematic variable of outgoing lepton momentum, \( p_l \) instead of reconstructed neutrino energy, and additionally uses weighting of pseudoexperiments 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 \( \bar{\nu}_e \) mode single-ring \( e \)-like sample in SK was 15, compared to a prediction of 16.8. The observed data \( \chi^2 \) value in the rate + shape analysis was 3.811 and the prediction was 6.3. The resulting \( p \) values are shown in Table I. Both the rate-only and rate + shape analyses disfavor the no-\( \bar{\nu}_e \) -appearance hypothesis (\( \beta = 0 \)) more than the PMNS \( \bar{\nu}_e \) appearance hypothesis (\( \beta = 1 \)). Compared to the prediction, a slightly weaker exclusion of the no-\( \bar{\nu}_e \) appearance hypothesis (\( \beta = 0 \)) is observed due to observing fewer events than expected. The rate + shape analysis gives a stronger observed exclusion of both hypotheses than the rate-only analysis, due to the extra shape information used to discredit each hypothesis.

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-\( \bar{\nu}_e \) -appearance case. The impact of this analysis is shown in the parameter space of \( P(\nu_\mu \rightarrow \nu_e) \) vs \( P(\bar{\nu}_\mu \rightarrow \bar{\nu}_e) \), 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 \( P(\nu_\mu \rightarrow \nu_e) = -P(\bar{\nu}_\mu \rightarrow \bar{\nu}_e) \) axis. The other oscillation parameters shift the ellipses along the identity line in the biprobability space. Two ellipses are shown in the left panel of 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 ellipses, the bottom right corresponds to \( \delta_{CP} = -\pi/2 \), top left to \( \delta_{CP} = \pi/2 \), and the middle to \( \delta_{CP} = 0, \pm \pi \).

Credible interval contours (68% and 90%) are produced by a Bayesian Markov chain Monte Carlo for the standard, fixed \( \beta = 1 \) parametrization and the new non-PMNS continuous-\( \beta \) parametrization. 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 ordering) 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 $P(\bar{\nu}_\mu \rightarrow \bar{\nu}_e)$ and $\bar{\nu}_e$, which is expected; the lower number of $\bar{\nu}_e$ than $\nu_e$ candidate events leads to a higher uncertainty in $P(\bar{\nu}_\mu \rightarrow \bar{\nu}_e)$, when not constrained by the PMNS model; additionally, the two probabilities are now decoupled due to the additional $\beta$ parameter, giving independent results for both probabilities and both event rates. These credible intervals can be used to compare other neutrino oscillation models against the fit constrained by the PMNS model and against the free $\beta$ fit that represents the information given by the T2K data with additional freedom.

The 90% and the 68% credible intervals from both continuous-$\beta$ and PMNS-constrained fits significantly overlap. There is good agreement between the two fits, showing consistency between T2K data and the PMNS model. Additionally, the value of $\beta$ is consistent with 1 (90% credible interval $[0.3, 1.06]$), when marginalizing over all other oscillation parameters. The data point is well within the 68% credible interval in both fits after including the statistical fluctuations.

**Conclusions.**—The T2K Collaboration has searched for $\bar{\nu}_e$ appearance in a $\bar{\nu}_\mu$ beam using a dataset 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 $\bar{\nu}_e$ appearance or $\bar{\nu}_e$ 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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