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New Results from the T2K Neutrino Oscillation Experiment

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Abstract The T2K experiment searches for the appearance of electron neutrinos in a muon neutrino beam. The rate of this process is sensitive to the neutrino mixing parameter θ_{13}. Recent measurements that $\theta_{13} \neq 0$ imply that $\nu_\mu \rightarrow \nu_e$ oscillations should be observable. Using all data through May 15, 2012 the T2K experiment has detected 10 candidate ν_e events, with an expected background for $\theta_{13} = 0$ of 2.73 ± 0.37 events. This 3.2σ excess of ν_e events is the strongest indication to date for appearance of electron neutrinos in a neutrino oscillation experiment, and for normal mass hierarchy and $\delta_{CP} = 0$ yields $0.059 < \sin^2 2\theta_{13} < 0.164$ at the 68% C.L.

Keywords T2K · neutrino oscillations · θ_{13}

1 Introduction

Numerous experiments have demonstrated conclusively that neutrinos undergo flavor oscillations and must therefore have small but non-zero masses [1]. Neutrino mass eigenstates can be related to neutrino flavor eigenstates by a 3×3 unitary mixing matrix known as the PMNS matrix. This matrix can be parametrized by three mixing angles θ_{12}, θ_{23} and θ_{13} that determine the amplitude of various oscillation probabilities, and one complex phase δ_{CP} that, if non-zero, would result in CP violation in neutrino oscillations. The

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distance over which neutrinos oscillate is determined by the mass splittings $\Delta m^2 = m_i^2 - m_j^2$ divided by the neutrino's energy E.

The mass splitting $|\Delta m^2_{32}| \approx 2.4 \times 10^{-3}$ eV^2 implies that neutrinos travelling a distance of 300 km will achieve their maximal oscillation probability for an energy of ~600 MeV. For a ν_μ beam the probability of oscillation into electron neutrinos is, in the absence of CP violation and in vacuum, given by

$$P_{vacuum}(\nu_\mu \to \nu_e) = \sin^2 2\theta_{13} \sin^2 \theta_{23} \sin^2 \left(\frac{1.27 \Delta m^2_{32} L}{E} \right) \quad (1)$$

where L is in km and E is in GeV. Measurements using reactor antineutrinos yield $\sin^2 \theta_{13} \approx 0.1$, implying a ~5% ν_e appearance probability at oscillation maximum [2,3]. The $\nu_\mu \to \nu_e$ oscillation, not previously observed, is therefore a testable prediction of standard neutrino oscillation theory with a long baseline neutrino experiment.

The oscillation probability is modified by both matter and CP effects. First, charged-current interactions of the ν_e component of the wavefunction with electrons with number density N_e in matter modify the oscillation probability from its value in vacuum to [4]

$$P(\nu_\mu \to \nu_e) \approx \left(1 + \frac{4\sqrt{2} E G_F N_e}{\Delta m^2_{32}} \right) P_{vacuum}(\nu_\mu \to \nu_e). \quad (2)$$

Secondly, non-zero δ_{CP} will modulate the oscillation probability in different ways for neutrinos and antineutrinos, as can be expressed in a CP asymmetry A_{CP} (see [5]):

$$A_{CP} = \frac{P(\nu_\mu \to \nu_e) - P(\bar{\nu}_\mu \to \bar{\nu}_e)}{P(\nu_\mu \to \nu_e) + P(\bar{\nu}_\mu \to \bar{\nu}_e)} \approx \frac{\Delta m^2_{12} L \sin 2\theta_{12}}{4E \sin \theta_{13}} \sin \delta_{CP}. \quad (3)$$

The resulting dependence of $P(\nu_\mu \to \nu_e)$ on δ_{CP} (see Eqn 3) and on the sign of Δm^2_{32} (see Eqn 2) is the major distinction between the method of measuring θ_{13} in long baseline experiments and the alternate method of using the disappearance of reactor neutrinos to estimate θ_{13}, which lacks dependence on these parameters. Long baseline neutrino experiments can therefore in principle probe θ_{13}, δ_{CP}, and the sign of the neutrino mass hierarchy (sgn Δm^2_{32}).

2 The T2K experiment

The Tokai-to-Kamioka (T2K) experiment ([6]) is a long-baseline neutrino oscillation experiment that uses a ν_μ beam produced at the JPARC accelerator in Tokai, Japan. A 30 GeV proton beam is directed onto a graphite target, and magnetic horns are used to focus positive charged hadrons, mostly π^+, into a ~100 m long decay volume. Pions decay in flight through $\pi^+ \to \mu^+ + \nu_\mu$ to produce a collimated ν_μ beam. The beam is directed 2.5° away from the Super-Kamiokande detector, lying 295 km away in western Japan (see Fig 1).

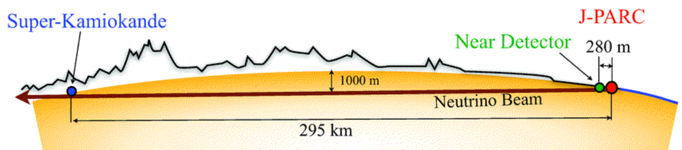

Fig. 1 Flight path of neutrinos at T2K.

The off-axis beam angle results in a neutrino energy spectrum peaking at 600 MeV, where the $\nu_\mu \rightarrow \nu_e$ oscillation is expected to be maximal.

A suite of off-axis near detectors called ND280 is used to measure the neutrino flux and energy spectrum near their production point before oscillations occur. ND280 uses the UA1 magnet operated at 0.2 T to measure the momentum of charged particles produced by neutrino interactions inside the detector. For the spectrum measurement the most important components of ND280 are two fine-grained scintillating detectors (FGDs, see [7]) consisting of 1 cm^2 square extruded polystyrene scintillator bars read out by wavelength-shifting fibers, and three large time projection chambers (TPCs, see [8]) using micromegas readout. By measuring the momentum and direction of leptons produced in charged-current interactions in the FGDs through the TPCs, the energy and flavor content of the beam can be measured. An on-axis detector named INGRID consisting of iron and scintillator measures the on-axis flux along a grid to determine the beam pointing [9].

Super-Kamiokande is a water Cherenkov detector with a fiducial mass of 22.5 ktonne [10]. Cherenkov rings produced by charged particles created by neutrino interactions are imaged using ~11,000 photomultiplier tubes and are used to reconstruct the direction and momentum of the resulting particles. Muons from ν_μ interactions can be distinguished from electron candidates by the sharpness of the Cherenkov ring, which for electron events will be diffuse due to smearing caused by multiple scattering of the electrons as they travel through the water.

Data Set T2K began data collection in spring 2010. Data-taking was interrupted by the major March 2011 earthquake in northeast Japan, but resumed in spring 2012. Preliminary results on ν_e appearance using 2010-2011 data were published in 2011 [11]. The data presented at this conference includes all 2012 data through May 15, 2012. This includes 1.43×10^{20} protons on target collected in 2010-2011, and an additional 1.13×10^{20} protons on target from 2012, for a total data size of 2.56×10^{20} protons on target[1].

[1] Subsequent to the conference at which these results were presented, T2K has analyzed ~20% more data and is in the process of preparing a full paper for publication. This data

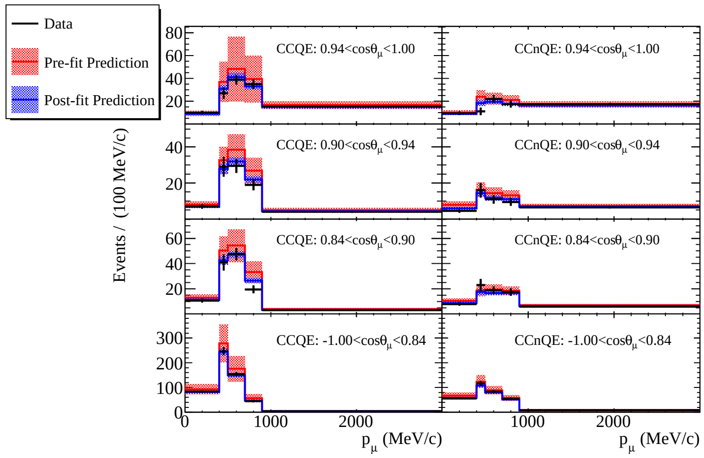

Fig. 2 Event rates in ND280 for quasielastic-like (left) and non-quasielastic-like (right) events, in four angular ranges, as a function of the muon's momentum. The red bands show the predicted number of events in each bin based upon the uncertainties in the beam flux and cross-section parameters. After fitting the ND280 data (solid lines), updated estimates of the beam flux and cross-section parameters are determined, which result in much smaller uncertainties in the event rates at ND280 (blue curves).

3 Beam and near detector analysis

The flux and energy spectrum of neutrinos produced in the beam can be predicted by modelling the production of charged hadrons on the graphite target, the magnetic focusing of these mesons by the horns, and the decay in flight of the mesons into neutrinos. The major factors affecting the flux prediction are the production rates and multiplicities of hadrons produced in the target. The NA61 experiment has measured hadronic production on graphite using a 30 GeV proton beam, and these measurements directly constrain the neutrino production rate at T2K [12]. A GEANT3 simulation, tuned to the NA61 data, is used to model the production of pions and kaons in the target, and NA61 data and data from other experiments are used to estimate the uncertainties in the flux. The major uncertainties are those in secondary nucleon production in the target, in the hadronic interaction length, and in the overall pion and kaon production rates. The neutrino energy spectrum in both Super-K and ND280 are calculated for ν_μ, ν_e, $\bar{\nu}_\mu$, and $\bar{\nu}_e$'s, along with the correlation matrix between the flux in the near detector and the flux at Super-K. (Because the decay volume looks like a line source of neutrinos at ND280 but a point source when viewed from Super-K, the fluxes in the two detectors are extremely similar but not identical.) The overall beam flux uncertainty, estimated from the

set gave consistent results to those presented here. In the interest of providing an accurate historical record of the conference, the results in these proceedings are those presented at the SSP 2012 conference. They should be considered "preliminary" until T2K's full paper is submitted and accepted for publication.

beam simulation, is $\sim$11%. At the beam's peak energy approximately 0.5% of events are intrinsic ν_e events in the beam.

The event rate seen in ND280 is the convolution of the flux with neutrino cross-sections. Measuring this rate as a function of the lepton momentum and angle constrains this convolution, and since both the energy spectra and cross-sections at Super-K are similar, ND280 measurements significantly reduce the uncertainties on the ν_e background predicted at Super-K as well as uncertainties on the signal rate. Negative muon-like tracks originating in ND280's first FGD and entering the following TPC are used to measure the ν_μ spectrum at ND280. Quasielastic events are separated from "other" events based on the presence of additional TPC tracks or Michel electrons in the latter. A maximum likelihood fit to the p_μ, θ_μ distribution of the selected events yields an estimate for the ν_μ flux in several energy bins as well as parametrized estimates of relevant neutrino interaction cross-sections. Prior constraints on the flux from the beam simulation estimates and on neutrino cross-sections from external experiments are included as priors in the fit by adding constraint terms to the log likelihood function. The resulting fit constrains both the flux parameters and cross-section uncertainties. Fig. 2 illustrates the significant reduction in the uncertainties on the event rates in ND280, where the red curves show the prior uncertainty on the quasielastic-like and "other" interaction rates in four angular bins as a function of momentum based upon the beam prediction and external cross-section constraints. The blue curves show the rate uncertainty after constraining to the ND280 data itself. The correlation matrix calculated from the beam simulation, along with the new constraints on cross-section parameters, are used to then predict the event distributions at Super-Kamiokande. Although only ν_μ events are used in the near detector, the ν_μ spectrum measurement constrains the ν_e flux at Super-K as well since the ν_μ rate constrains the hadron production rates that produce both flavors.

4 Selecting ν_e events at Super-Kamiokande

Candidate ν_e events are selected at Super-Kamiokande as described in [11]. Events are selected that are in-time with the beam bunch structure, correcting for the time-of-flight from Tokai to Kamioka. Fully contained events inside Super-Kamiokande's 22.5 ktonne fiducial volume are then selected. Candidate events are required to have a single reconstructed Cherenkov ring with an electron-like particle identification, to have a visible energy in excess of 100 MeV, and to have no following decay electron. These cuts are designed to select primarily charged-current quasielastic events due to ν_e interactions. An important detector background comes from misreconstructed π^0 decays, with the π^0 often produced through a neutral current process such as $\nu + N \rightarrow \nu + N + \pi^0$. Such π^0's decay to two gamma-rays, producing in principle two electron-like Cherenkov rings. However, if one of the rings is very low in energy due to asymmetric decay in the lab frame, or if the two rings overlap, only a single ring may be reconstructed. To reduce this background,

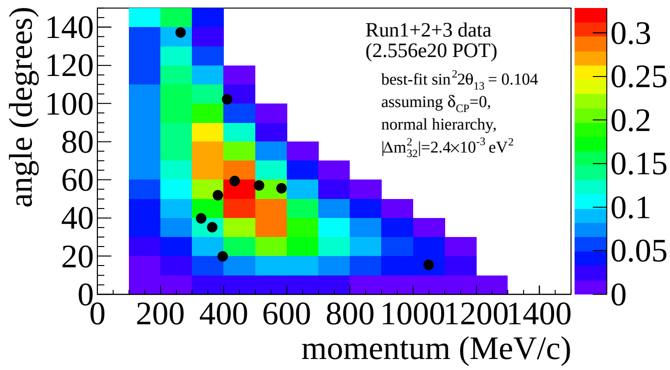

Fig. 3 Momentum and electron angle for candidate ν_e events at Super-Kamiokande. The ten black points correspond to the 10 events seen in data. The colored contours show the expected distribution of signal and background events (dominated by signal) at the best-fit value of $\sin^2 2\theta_{13} = 0.104$.

every single-ring electron-like event is fitted for the best secondary electron ring that can be fitted to the event, and the invariant mass of the two rings, calculated on the assumption that they come from a π^0 decay, is required to be less than 105 MeV. A last cut to reduce backgrounds is to require that the reconstructed energy of the neutrino, calculated from the reconstructed momentum and direction of the single ring under the hypothesis that the electron was produced in a quasielastic interaction, must be less than 1250 MeV. This tends to reject intrinsic beam ν_e backgrounds, which often result from charged kaons that are focused by the beam horns and which decay into higher energy neutrinos, while accepting signal ν_e events from oscillation, which are expected to peak at the energy of maximum oscillation near 600 MeV.

Applying these cuts to the current data yields 10 candidate ν_e events. The reconstructed momenta and angles of the electrons are plotted in Figure 3.

5 Oscillation result & conclusions

If $\theta_{13} = 0$, the expected rate of ν_e candidates at Super-Kamiokande would be 2.73 ± 0.37 events. About 52% of this background is due to intrinsic ν_e's in the beam produced by rare meson decays, while 37% is due to misidentified ν_μ events in Super-K, dominated by π^0 events that are misreconstructed as single-ring events. The remaining background is due to small antineutrino contributions and a small oscillation contribution from second-order oscillations through the solar oscillation parameters Δm^2_{12} and θ_{12}. The uncertainty in the background rate is estimated from toy Monte Carlo including detec-

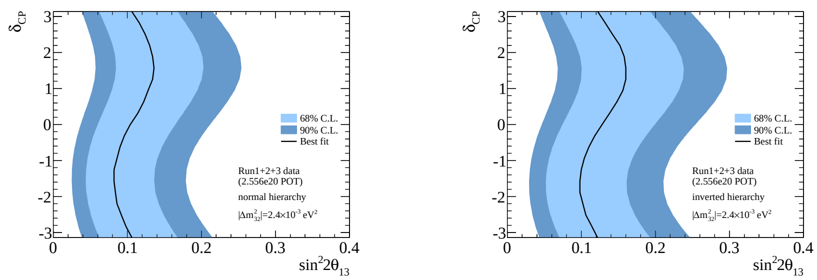

Fig. 4 58% and 90% confidence level contours in δ_{CP} vs. $\sin^2 2\theta_{13}$, for normal mass hierarchy ($\Delta m^2_{32} > 0$, left) and inverted hierarchy ($\Delta m^2_{32} < 0$, right). The value $\theta_{13} = 0$ is excluded at 3.2σ significance.

tor efficiency and misidentification systematics at Super-K as well as flux and cross-section uncertainties from the beam+ND280 fit.

Given the expected ν_e background of 2.73 ± 0.37 events for $\theta_{13} = 0$, the probability of observing 10 or more events is 8×10^{-4}, equivalent to a 3.2σ excess. This result is the first indication at greater than 3σ significance for the appearance of ν_e events in a long-baseline ν_μ beam.

Oscillation parameters are determined from a maximum likelihood fit of the two-dimensional p, θ distribution of the candidate ν_e events. Probability distributions for (p, θ) are calculated for signal events and each background source as a function of θ_{13} and δ_{CP} for each choice of neutrino mass hierarchy. Fig 4 shows the resulting oscillation contours in $(\theta_{13}, \delta_{CP})$ for normal and inverted hierarchies. For normal hierarchy and $\delta_{CP} = 0$, the best=fit value of θ_{13} is $\sin^2 2\theta_{13} = 0.104$, and the 68% confidence level region is $0.059 < sin^2 2\theta_{13} < 0.164$. These results are consistent with recent determinations of θ_{13} from reactor antineutrino experiments at km-scale baselines [2, 3].

Future T2K data will sharply reduce the uncertainty on the rate of $\nu_\mu \rightarrow \nu_e$ oscillations. The establishment of a non-zero rate for this process will then make feasible CP violation studies in which the rate of $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ oscillation is measured and compared to the rate for neutrinos to determine the value of δ_{CP}. Such efforts will likely require megatonne-scale detectors with megawatt-scale beam power, but remain the most promising means of detecting CP violation in the neutrino sector.

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