Searches for sterile neutrinos using the T2K off-axis near detector

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1 Introduction

The results from a number of short baseline (SBL) neutrino experiments \cite{1, 2} and the reanalysis of previous reactor experiments with updated antineutrino fluxes \cite{3} suggest some incompatibility with the standard three-neutrino model (the gallium and reactor anomalies). A possible solution is the existence of sterile neutrinos \cite{4}: right-handed particles that do not interact via the weak interaction. Their existence can be studied through their mixing with the three active Standard Model neutrinos. The 3+1 model assumes there is only one sterile neutrino whose mixing is described by a unitary $4 \times 4$ matrix. If the mass squared difference $\Delta m_{41}^2$ is much larger than the other mass differences ($\mathcal{O}$ 1 eV$^2$) the mixing can lead to SBL oscillations. The survival probability is given by

$$P(\nu_\alpha \rightarrow \nu_\alpha) = 1 - \sin^2 2\theta_{\alpha\alpha} \left( \frac{1.27\Delta m_{41}^2 L_{\nu}}{E} \frac{[\text{GeV}]}{[\text{eV}]^2[\text{km}]} \right)$$

where $L_{\nu}$ and $E$ are the flight path and energy of the neutrino respectively.

The existence of sterile neutrinos can be probed with the T2K Experiment \cite{5}: a long baseline neutrino oscillation experiment in Japan. Protons impinge on a graphite target, producing a beam of 90% $\nu_\mu$, 8.8% $\bar{\nu}_\mu$, 1.1% $\nu_e$ and 0.1% $\bar{\nu}_e$. Neutrinos are detected at a near detector complex 280 m from the target, and at the Super-Kamiokande far detector 295 km from the target. The near detector complex consists of two detectors, one situated on-axis (INGRID) and one situated 2.5° off-axis (ND280). At ND280 the $\nu_\mu$ component of the beam is peaked at 600 MeV/c and the dominant interaction is charged current (CC) quasi-elastic (QE) scattering ($\nu n \rightarrow l^- p$). At higher energies pions are produced in CC resonant single pion production (CCRES), coherent pion production (CCCoH) and multi pion production due to deep inelastic scattering (CCDIS).

Here we present a search for $\nu_e$ disappearance using ND280. The data analysed corresponds to an exposure of $5.9 \times 10^{20}$ protons on target (POT). We also present an introduction to a new analysis looking for $\nu_\mu$ disappearance with ND280, which promises to have interesting results in 2015.
2 Search for short baseline oscillations using ND280

To search for SBL oscillations, binned templates are built using the Monte Carlo (MC) reconstructed energy distribution assuming CCQE interactions. The templates can be weighted event-by-event with the oscillation probability to determine the dependence on the oscillation parameters of a given model. The oscillation probability affects the signal events based on the true energy and flight path of the neutrino. These templates are then compared to data in a binned likelihood ratio fit with systematic errors included as nuisance parameters with gaussian constraints, similar to other T2K analyses [6].

2.1 Search for short baseline $\nu_e$ disappearance

At ND280 the 3+1 model is investigated with $U_{\mu 4} = 0$ in order to investigate the gallium and reactor anomalies. A sample of $\nu_e$ events is selected with a purity (efficiency) of 63% (26%) [7]. The largest background comes from CCDIS or neutral current interactions where a $\pi^0$ is produced ($\nu_\mu N \rightarrow \pi^0 X$). A control sample is used to measure this background, predominantly consisting of photon conversions from $\nu_\mu N \rightarrow \pi^0 X$ in neutral current and CCDIS interactions, with a purity (efficiency) of 92% (12%).

A measurement of $\nu_\mu$ CC interactions at ND280 is used to reduce the flux and the correlated cross-section uncertainties, as described in [6]. The sample of $\nu_\mu$ CC interactions is subdivided into events without charged pions (CC0$\pi$), events with one positive pion (CC$\pi^+$) and other interactions that produce pions (CCOth). This provides sensitivity to the rate of $\nu_\mu$ CCQE, CCRES and CCDIS interactions.

![Figure 1: Reconstructed energy distributions of the $\nu_e$ (left) and control (right) samples broken down by $\nu_e$ interactions (signal), backgrounds inside and outside the fiducial volume due to $\nu_\mu N \rightarrow \pi^0 X$ (In-FV and OOFV respectively), and all other sources of background ($\nu_\mu$ other). The ratio of data to MC in the null oscillation hypothesis is shown. The red error band corresponds to the fractional systematic uncertainty. Black dots represent the data with statistical uncertainty.](image)

The results from this analysis are based on data taken from January 2010-May 2013 (corresponding to $5.9 \times 10^{20}$ POT). Figure 1 shows the reconstructed energy distributions
of the $\nu_e$ signal and control samples. From the likelihood fit to data the best fit oscillation parameters are $\sin^2\theta_{ee} = 1$ and $\Delta m^2_{\text{eff}} = 2.05 \text{eV}^2/c^4$ \cite{8}. The 2D confidence intervals in the $\sin^2\theta_{ee}-\Delta m^2_{\text{eff}}$ parameter space can be seen in Figure 2\footnote{The p-value of the null hypothesis is 0.085.}. The T2K best fit is marked by a green star, and those of other experiments by filled circles of the same colour as the corresponding limits.

Figure 2: The T2K exclusion region for $\nu_e$ disappearance at 95\% CL compared with other experimental results: allowed regions of gallium and reactor anomalies and excluded regions by $\nu_e$- carbon interaction data and solar neutrino data \cite{9}. The T2K best fit is marked by a green star, and those of other experiments by filled circles of the same colour as the corresponding limits.

2.2 Search for short baseline $\nu_\mu$ disappearance

The signal sample for this analysis is the same as the $\nu_\mu$ CC sample described in Section 2.1, binned in terms of the reconstructed neutrino energy assuming CCQE interactions and input into the likelihood fit described above.

Figure 3 shows the expected sensitivity for a 3+1 analysis, at 90\% CL, when flux and cross-section systematics are evaluated, compared to other experimental results. These preliminary results are promising. Once the detector systematics and final state interaction systematics have been included the data will be analysed.

3 Summary

A search for $\nu_e$ disappearance caused by SBL oscillations has been performed with the T2K off-axis near detector. The exclusion region at 95\% CL is approximately given by $\sin^2\theta_{ee} > 0.3$ and $\Delta m^2_{\text{eff}} > 7 \text{eV}^2/c^4$. The p-value of the null oscillation hypothesis is 0.085. These results exclude parts of the gallium anomaly and a small part of the reactor anomaly allowed regions. The analysis is limited by statistical uncertainties and therefore further data from T2K will help to improve the analysis.

Searches for $\nu_\mu$ disappearance due to SBL oscillations are being constructed. A full MC
Figure 3: The expected sensitivity for $\nu_\mu$ disappearance, at 90% CL, based on $3 \times 10^{20}$ POT of MC scaled to $6 \times 10^{20}$ POT with flux and cross-section systematics included. The red and the yellow lines show the 90% CL when the CC0$\pi$, CC$\pi^+$ and CCOth samples are combined into a single CC inclusive sample. The dashed purple line shows the 90% CL when the three samples are kept separate. The shaded region indicates the 90% CL limits from the CCFR [10] and CDHS [11] experiments. The black line represents the 90% CL limits from MiniBooNE/SciBooNE measurements [12].

sensitivity study with systematic uncertainties is almost complete for the 3+1 model and promises to have interesting results in 2015.

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