

The Upgrade of the T2K Near Detector



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1 Introduction

The T2K (Tokai-to-Kamioka) experiment is a world leading long baseline oscillation experiment. It discovered non-zero θ_{13} mixing angle with accelerator neutrinos, obtained CP violation hints in neutrino sector [1], and has leading sensitivities in Δm_{23}^2 and θ_{23} octant. An off-axis high-intensity neutrino beam is produced in J-PARK, the near detector complex measures the beam parameters, and then oscillated neutrino beam is measured in the far detector Super-Kamiokande. The ND280 is an off-axis near detector. Three time-projection chambers (TPCs) and two Fine-Grained Detectors (FGDs) form a tracking system which together with a π_0 detector (P0D) is covered by electromagnetic calorimeters, and a solenoid coil. Side Muon Range Detectors (SMRD) are embedded in the iron yokes of the magnet. Magnetic field is 0.2 T. The schematic view of ND280 is shown in Fig. 1 (left). The role of ND280 is to tune and constrain the flux and cross-section systematics model by selecting neutrino interactions before the oscillations. The impact on T2K oscillation analysis is dramatic: systematic uncertainties are reduced from 15–20% to $\sim 5\%$. Despite a significant success in systematic uncertainties reduction, the initial ND280 design has its limitations. ND280 has a non-isotropic detection efficiency in comparison to 4π sensitivity in the Super-Kamiokande detector. The detection threshold for protons is about 450 MeV/c (~ 100 MeV E_{kin}) which is relatively high. Moreover

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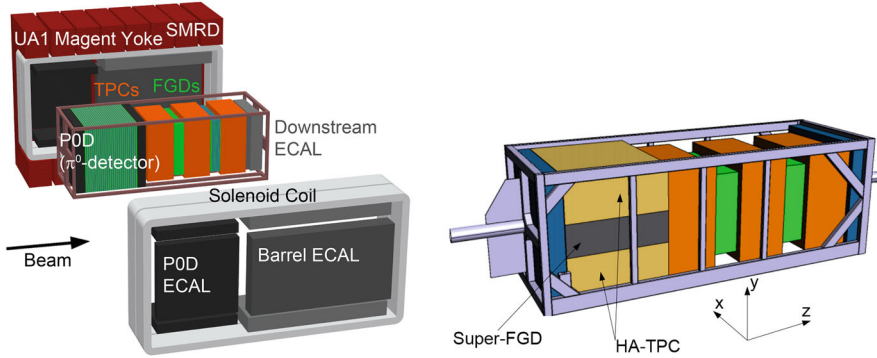


Fig. 1 The schematic view of the initial Near Detector complex (left) and the proposed upgraded configuration (right) with the SuperFGD and HA-TPCs. The ECAL, solenoid coil, magnet yoke and SMRD will be kept at place but are not shown as well as the ToF planes

ND280 is not capable to detect neutrons. Hadronic information is essential to improve neutrino interaction modelling and hence the energy reconstruction for the oscillation analysis.

The upgrade of ND280 [2] is intended to handle these limitations and to substantially improve systematics. The POD detector is replaced by a setup of detectors: a new scintillator target (SuperFGD), two High-Angle TPCs (HA-TPCs) and a Time-of-Flight (ToF) detector. See Fig. 1 (right).

2 New Detectors

2.1 The SuperFGD Detector

The SuperFGD (Super Fine-Grained Detector) is a fully active and highly granular scintillator neutrino detector. While FGDs consist of long scintillation strips, which do not allow reconstruction of high-angle tracks, SuperFGD consists of ~ 2 million scintillation cubes, which allow reconstruction of particles going in all directions. Polystyrene cubes are injection-molded, doped with PTP (1.5%) and POPOP (0.01%) and have reflector coating. Each cube has three drilled holes going in orthogonal projections. Scintillation light is collected by 1 mm Kuraray Y-11(200) MS wave-length shifting (WLS) fibers. Silicon photo-multipliers (SiPMs) are placed at one side of each WLS fiber and are used to read signals (model: S13360-1325PE Hamamatsu MPPC). A free side of each fiber is connected to a LED calibration system. Multiple beam tests of prototypes have been performed to characterize the SuperFGD performance [3, 4]. The ($8 \times 24 \times 48 \text{ cm}^3$) prototype was tested at the beam in CERN [5]. The raw light yield was 53.7 p.e. (51.0 p.e.) per MIP for events recorded on channels with the 8 cm (24 cm) fibers. For the long

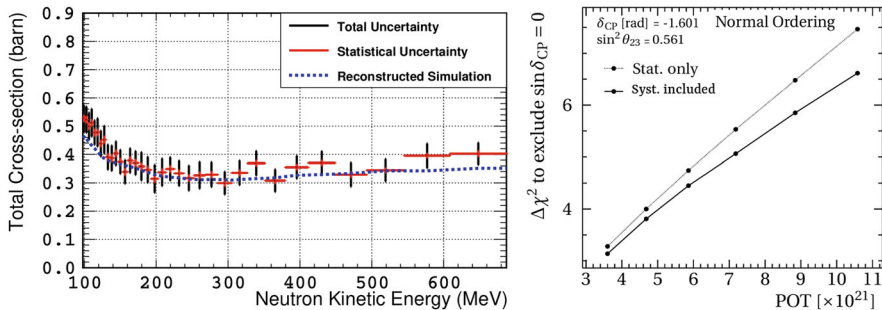


Fig. 2 Left: The total neutron-CH cross section as a function of neutron kinetic energy. The black vertical bars represent the total uncertainty and the red the statistical uncertainty. The Geant4 Bertini model is shown in blue. Right: Sensitivity to Charge-Parity violation as a function of Protons-on-Target when considering only statistical uncertainties (dotted) and when using the systematic uncertainties with new detectors constraints (solid)

fibers which were parallel to the beam direction energy released in several cubes contributes to a signal in one channel making it difficult to determine the light yield. Optical crosstalk was found to be 2.94% per cube side. The dE/dx resolution for a single cube is 25% and improves up to 10% for longer tracks. It was demonstrated that one channel time resolution is better than 1 ns, further improved with higher amplitudes and larger number of channels [6].

Two SuperFGD prototypes ($8 \times 24 \times 48 \text{ cm}^3$ and $8 \times 8 \times 32 \text{ cm}^3$) were exposed to a neutron beam at LANL. This is an important measurement to demonstrate a neutron detection capability in an energy range relevant for T2K [7]. Neutron energy is reconstructed using time-of-flight information between the arrival of gammas and neutron secondary interaction. For such type of measurements time resolution is a crucial factor. It was tested that like in case of muons averaging information from different channels allows to improve time resolution by a factor of \sqrt{N} where N is a number of channels. For selected neutron events with at least 3 cubes intrinsic time resolution is about 0.5 ns (using time measurements from fibers orthogonal to the beam direction). The improvement in the neutrino flux constraints due to the ability of neutron energy reconstruction is discussed in [8] In the presence of neutron-nucleus interactions, the signal event rate decreases exponentially along the coordinate parallel to the beam. This allows to measure the neutron cross-section as a function of its kinetic energy (see Fig. 2, left).

2.2 High-Angle Time Projection Chambers

Two new additional “horizontal” TPCs will surround the SuperFGD detector from the top and bottom sides. Their configuration allows the identification and momentum reconstruction for up and downward going tracks with respect to the

neutrino beam, which is complementary to the forward-going particle information from the current, vertical TPCs. The design of HA-TPCs is similar to the existing ND280 TPCs. The main differences to the existing TPCs are the replacement of the standard bulk-MicroMegas with new resistive bulk-MicroMegas and a new field cage design to minimize dead space and maximize the tracking volume. Encapsulated Resistive Anode Micromegas (ERAM) with grounded mesh and anode at a positive amplification voltage provide several advantages. Since the charge is spread over several pads the spatial resolution is improved by a factor of $\sqrt{12}$. This allows to use larger pads for the same spatial resolution as for the bulk Micromegas detectors. Insulation of the resistive anode from the pads suppresses formation of sparks and limits their intensity. Therefore, it is possible to get rid of the cumbersome anti-spark protection circuitry. Another advantage of the anode encapsulation is that the detection plane is fully equipotential. This leads to more uniform field, less track distortions, and module flexibility.

Characterization of the charge spreading (RC), gain of ERAMs using X-rays, measurements of the spatial and dE/dx resolution were performed in several test beam campaigns at CERN and DESY: [9–11]. Achieved spatial resolution is better than 800 μm and the dE/dx resolution is better than 10% for all track angles and drift distances of interest for T2K.

2.3 Time-of-Flight Detectors

Time-of-Flight system consists of 6 planes of $2.3 \times 2.5 \text{ m}^2$ size, each plane is made of 20 plastic scintillator bars. These planes fully envelope the SuperFGD and High-Angle TPCs. Each scintillator bar is read out on both ends with an array of 8 SiPMs. An average time resolution of about 0.14 ns is achieved for a single bar when measured with cosmic muons [12]. This result is very important to determine the direction of particles and the vertex time, and therefore to suppress backgrounds.

3 Summary

The main goal of the ND280 upgrade is to reduce systematic uncertainties associated with neutrino flux and cross-section modeling for future studies of neutrino oscillations. The upgraded ND280 detector will be able to perform a full exclusive reconstruction of the final state from neutrino-nucleus interactions, including measurements of low momentum protons ($\sim 50 \text{ MeV } E_{kin}$), pions and for the first time, event-by event measurements of neutron kinematics. The physics sensitivity that can be expected from the upgraded detector is described in [13]. The expected sensitivity to Charge-Parity violation searches for the level of systematics expected after the ND280 upgrade is shown in Fig. 2, right.

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