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The T2K fine-grained detectors

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ABSTRACT

T2K is a long-baseline neutrino oscillation experiment searching for ν_e appearance in a ν_μ beam. The beam is produced at the J-PARC accelerator complex in Tokai, Japan, and the neutrinos are detected by the Super-Kamiokande detector located 295 km away in Kamioka. A suite of near detectors (ND280) located 280 m downstream of the production target is used to characterize the components of the beam before they have had a chance to oscillate and to better understand various neutrino interactions on several nuclei. This paper describes the design and construction of two massive fine-grained detectors (FGDs) that serve as active targets in the ND280 tracker. One FGD is composed solely of scintillator bars while the other is partly scintillator and partly water. Each element of the FGDs is described, including the wavelength shifting fiber and Multi-Pixel Photon Counter used to collect the light signals, the readout electronics, and the calibration system. Initial tests and *in situ* results of the FGDs' performance are also presented.

1. Introduction

The Tokai-to-Kamioka (T2K) experiment [1] is studying neutrino oscillations using a man-made neutrino beam sent from the Japan Proton Accelerator Research Complex (J-PARC) in Tokai, Japan, towards the Super-Kamiokande detector [2], located 295 km away. T2K is the first experiment to make use of an off-axis configuration [3–5], which provides a relatively narrow band beam, in this case peaked around 700 MeV. A magnetized near detector called ND280, situated 280 m downstream from the hadron production target in J-PARC, measures the neutrino beam's properties before the neutrinos have had a chance to oscillate. It can therefore be used to predict the neutrino event rate and energy spectrum at Super-Kamiokande in the absence of oscillations. As well, interaction rates or cross-sections for several neutrino reaction channels in the 100 MeV to few GeV energy range will be measured.

1.1. Description of ND280

ND280 contains several subdetectors optimized to measure neutrino interactions in this energy range [6]. This paper describes the design and performance of ND280's two massive fine-grained detectors (FGDs), which provide target mass for neutrino interactions as well as tracking of charged particles emerging from the interaction vertex. The FGDs form part of ND280's tracker. The tracker, consisting of three large time projection chambers (TPCs) [7] and the two FGD modules, lies at the heart of ND280 (see Fig. 1). The primary function of ND280 is to measure the neutrino beam's flux,

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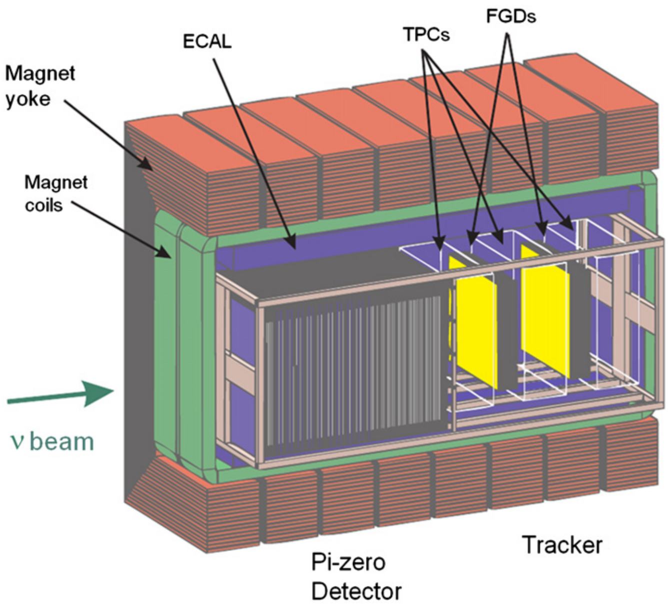

Fig. 1. Cutaway view of the ND280 detector. The two FGDs are located between three TPCs. A Pi-Zero Detector sits upstream of the tracker region, and electromagnetic calorimeters (ECAL) surrounds all of the central detectors. The magnetic field is in the horizontal direction perpendicular to the beam.

energy spectrum, and flavor composition by observing charged current neutrino interactions. The FGDs are thin enough ($\sim$30 cm) that most of the penetrating particles produced in neutrino interactions, especially muons, reach the TPCs where their momenta and charges are measured by their curvature in the $\sim$0.2 T magnetic field. While the TPCs provide excellent 3D tracking and particle identification for forward- and backward-going charged particles, short-ranged particles such as recoil protons are primarily measured in the FGDs themselves. The FGDs therefore have fine granularity so that individual particle tracks can be resolved and their directions measured.

1.2. Tracker measurement goals

An especially important reaction to measure is the CCQE interaction $\nu_\ell + n \rightarrow \ell^- + p$, which is the most common interaction at T2K's beam energy. For these interactions, the energy of the incident neutrino is calculable from only the energy and direction of the final lepton, with an accuracy limited by the Fermi momentum of the neutron in the nucleus. The CCQE interaction cross-section is relatively simple to model theoretically [8], and is well constrained by data [9–11]. CCQE interactions therefore provide an ideal means of measuring the neutrino beam's energy spectrum and flux in the near detector, which can then be used to predict the event rate and energy spectrum at the far detector.

Although the CCQE interaction is the most common interaction mode, many other processes occur. An important example is CC single pion (CC-1π) production ($\nu_\ell + N \rightarrow \ell^- + N' + \pi$). This process often proceeds through excitation of a Δ resonance and is indistinguishable from a CCQE event in Super-K, where only the final state charged lepton is above the Cherenkov threshold. Because CC-1π produces a three-body final state, the initial neutrino's energy is not a simple function of the charged lepton's direction and energy. CC-1π events will therefore smear out the energy spectrum measurement, and every effort is made to exclude them from the energy spectrum analyses in both the near and far detectors. At Super-K this is accomplished by selecting only events with a single charged lepton in the final state, although CC-1π events with the pion below Cherenkov threshold form an irreducible background. The ND280 tracker is used to measure the size of this and other backgrounds to CCQE interactions at Super-K.

The rates of these CCQE and non-QE interactions from the T2K beam must be well determined in the tracker so that a satisfactory prediction can be made of the unoscillated event rates at Super-K. Because the tracker can see all charged particles produced in an interaction, it can identify CCQE events by selecting just those events which contain a lepton and a recoil proton. Events containing pions can be rejected by searching for additional charged tracks near the vertex, identifying Michel electrons produced by pions stopping in an FGD through the $\pi \rightarrow \mu \rightarrow e$ decay chain, or by testing the consistency of a track's deposited charge, direction, and momentum with the CCQE hypothesis.

1.3. FGD design criteria

The FGDs must therefore satisfy a variety of design criteria:

- They must be capable of detecting all charged particles produced at the interaction vertex with good efficiency in order to determine the type of interaction.
- They must be thin enough that charged leptons will penetrate into the TPCs where their momenta and flavor can be determined.
- The directions of recoil protons must be measured so that CCQE events can be selected using kinematic constraints on the recoil proton's direction.
- Particle ID from dE/dx measurements must distinguish protons from muons and pions.
- The tracker must contain $\sim$1 t of target mass for neutrino interactions in order to yield a sufficient statistical sample of events.
- Because the ND280 sits in an off-axis beam, the off-axis angle and hence the neutrino energy spectrum varies substantially across the face of the tracker. Nonuniformities in threshold or efficiency across the tracker would greatly complicate the extraction of the neutrino beam properties and could potentially bias the measurement. Therefore, the detector response across the tracker needs to be as uniform as practically possible.
- Because the far detector is a water Cherenkov detector, the tracker must measure the neutrino interaction rates on water. All of the relevant neutrino cross-sections depend at some level on the target nucleus through such effects as Pauli blocking, pion rescattering and absorption inside the nucleus, etc. These nuclear effects cannot be reliably corrected for from theory, and therefore the nuclear interaction rates must be measured on water so that the rates can be used to predict the rates for these processes in Super-K.
- The FGD electronics must provide for acceptance of late hits such as those due to Michel electrons.

1.4. Overview of the FGD design

The functional unit of an FGD is a single extruded polystyrene scintillator bar (described in Section 2) oriented perpendicular to the beam in either the x or y direction. To achieve the necessary fine granularity, the bars have a square cross-section 9.6 mm on a side. They are arranged into modules, each "XY module" consisting of a layer of 192 scintillator bars in the horizontal direction glued to 192 bars in the vertical direction (see Section 3). FGD1 contains 15 such modules while FGD2 contains seven. Each module has dimensions of $186.4 \times 186.4 \times 2.02$ cm (not including electronics). Each scintillator bar has a reflective coating containing TiO_2 and a wavelength shifting (WLS) fiber (Section 4) going down an axial hole. An air gap provides the coupling between the scintillator and fiber. The fiber extends a few centimeters from