Development of a 3D highly granular scintillator neutrino detector for the T2K experiment

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Saba PARSA
University of Geneva
on behalf of T2K ND280 Upgrade Collaboration
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1. Introduction

T2K experiment Near Detectors
Motivation for Upgrade
ND280 Upgrade Configuration
T2K Experiment

- Oscillation analysis of $\nu_\mu \rightarrow \nu_e$ and $\nu_\mu \rightarrow \nu_\mu$ with high intensity accelerator beam.
- Off axis technique (2.5 degree) ensures a narrower beam energy spectrum.
- $E_\nu \sim 700$ MeV, Oscillation distance: 295 Km
- Large backgrounds in neutrino and Anti-neutrino beams mode.
Current Near Detector (ND280)

The ND280 detectors play a significant role in the reduction of flux and cross-section systematics in T2K oscillation analyses. Since 2009 they have performed very well. However, the current design configuration does have limitations.

Neutrino interactions at near detector (Quasi-elastic candidate)

Neutrino interactions at far detector

Systematics for FHC

<table>
<thead>
<tr>
<th>Source of uncertainty</th>
<th>$\delta N/N$ (CCQE-like)</th>
<th>$\delta N/N$ ($\nu_\mu$)</th>
<th>$\delta N/N$ ($\nu_e$ CC1$\pi^+$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Flux</td>
<td>3.7%</td>
<td>3.6%</td>
<td>3.6%</td>
</tr>
<tr>
<td>Cross section</td>
<td>5.1%</td>
<td>4.0%</td>
<td>4.9%</td>
</tr>
<tr>
<td>Flux + cross section</td>
<td>11.3%</td>
<td>10.8%</td>
<td>16.4%</td>
</tr>
<tr>
<td>(w/o ND280 constraint)</td>
<td>4.2%</td>
<td>2.9%</td>
<td>5.0%</td>
</tr>
<tr>
<td>(w/ ND280 constraint)</td>
<td>2.5%</td>
<td>1.5%</td>
<td>10.5%</td>
</tr>
<tr>
<td>FSI + SI + PN at SK</td>
<td>2.4%</td>
<td>3.9%</td>
<td>9.3%</td>
</tr>
<tr>
<td>SK detector</td>
<td>12.7%</td>
<td>12.0%</td>
<td>21.9%</td>
</tr>
<tr>
<td>(w/o ND280 constraint)</td>
<td>5.5%</td>
<td>5.1%</td>
<td>14.8%</td>
</tr>
<tr>
<td>(w/ ND280 constraint)</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

521.8 exp. no osc.
135 observed
Current Near Detector (ND280)

Basket Components:

POD ($\pi^0$ detector): Scintillator planes interleaved with lead/brass

Tracker section:
Two FGDs (Fine Grained Detectors)
- Thin, wide scintillating planes.
- Provides active target mass
Three TPCs (Time Projection Chambers)
- Excellent measurement of charged particles.
ND280 Advantages and Limitations

- Magnetized -> Rejection of wrong sign beam component by magnetic field
- Active target (FGD) -> Interaction vertex detection
- TPCs -> 3D track reconstruction, charge, momentum and particle ID

Particle ID from $dE/dx$ in TPC
ND280 Advantages and Limitations

✗ ND280 has Limited angular acceptance for high angle and backward tracks, SK has 4π acceptance.
✗ Poor detection efficiency for e <1 GeV (\(\gamma\) conversion contamination)
✗ No track direction determination: Large out of Fiducial Volume background

Reconstructed momentum and angle for muons selected at ND280 (Left) and electrons selected at SK (right).
ND280 upgrade configuration

- Re-design of the upstream part of Basket components:
  - Super FGD: A novel 3D highly granular plastic scintillator target
  - Two horizontal High-Angle TPCs
  - Time of Flight planes all around

- Current downstream tracker (FGDs + TPCs) unchanged
2. Super FGD
A 3D plastic scintillator detector

Expected performance from simulations
Assembly Challenges
Optical Interface
Electronics
Super FGD is a novel detector design consisting of small scintillating cubes read out with WLS fibers in three orthogonal directions.

- Active tracking volume consist of 2 Million 1 cm-sized plastic scintillator cubes
- Mass 2 tons \((1.92 \times 1.92 \times 0.56 \text{ m}^3)\).
- Clean measures of momentum-balance in transverse plane
- \(4\pi\) acceptance
- 3D readout with \(6 \times 10^4\) channels (MPPC).
- Detection of activity around vertex
Expected performance from simulations

Reconstruction efficiency

- High reconstruction efficiency in all directions (90% for muons)
- Lower detection threshold for protons (~300 MeV)
Expected performance from simulations

\(\gamma\) Conversion background

- Disentangling electrons (\(\nu_e\) signal) from photon conversion.
- Disentangling one/two track in a cube by comparing energy deposit.
Expected performance from simulations

Angular acceptance

- Larger **angular acceptance** with new TPCs and TOF

Nuclear effects

- Better studying of nuclear effects thanks to low momentum threshold and full angle coverage.
- Impact on T2K oscillation analysis:

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Reduction of the uncertainty</th>
</tr>
</thead>
<tbody>
<tr>
<td>Flux</td>
<td>20 %</td>
</tr>
<tr>
<td>$\sigma_v$ (CCQE/2p2h)</td>
<td>20% - 40%</td>
</tr>
<tr>
<td>FSI</td>
<td>45 %</td>
</tr>
<tr>
<td>$\sigma_v$ (Q^2 dependent)</td>
<td>25 %</td>
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</tbody>
</table>
Expected performance from simulations

Neutron Detection

- Preliminary study shows high Neutron detection efficiency in Super FGD

-> A Neutron beam test is foreseen at Los Alamos (LANSCE) to validate this study
Production and assembly challenges

- Injection (12 cube mold)
- Etching (Chemical reflector)
- Drilling (3 holes per cube)
Production and assembly challenges

- Happening now at INR

4. **Cube beads**  
   (192 cubes on a fishing line)

5. **Cube Sheet**  
   (192 x 192 cubes)
Production and assembly challenges!!!

5. Sewing the layers
   (~ 2 Million cubes!)
6. Replace fishing line with WLS fiber
   (~ 60k fibers!)

This is the prototype assembly for CERN beam test (size: 48x24x8 cm³)
The cubes are to be held mechanically in place
Carbon Fiber sandwich with AIREX foam cover all faces
There are holes on all faces for the fiber to go through
Optical interface

- PCB units with 8x8 surface mount MPPCs
- Hamamatsu MPPC: (S13360-1325PE)
- Fibers are read out from one end
- Light injection system on the free end of fiber for calibration
Electronics

- 4 CITIROC chips per FEB (Based on Baby Mind electronics)
- FEB size: 20cm x 27.5cm
- FEB’s per side: 228... (456 in total!!)
- Cooling is required

![Diagram of CITIROC and FEB components]
3. Super FGD Prototype
At CERN beam test 2018

Beam test setup
Event displays
Cube response to MIP
Stopping Proton
Time resolution
Beam test at CERN-PS

- 48x24x8 cubes assembled in INR
- Photo detection with Hamamatsu MPPCs
- Readout electronic based on CITIROC chip (BabyMIND electronics)
- Calibration with LED pulse generator
- Beam energy 0.5 – 8 GeV
- Magnetic field 0.2-0.7 T
Event displays

**Pion (π) candidate**

- **γ conversion candidate**
  - Stopping proton candidate
  - ToT [2.5 ns]
  - Z [cm]

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20/2/19
Signal path and Calibration method

**Calibration method**

- Extract LG calibration factors by fitting against HG data (roughly linear)
- Extract HG calibration ratio ADC/pe from MPPC fingerplots
- Extract ToT calibration factors by fitting against HG and LG data (non-linear)

**Sampling of rising and falling edges of individual trigger outputs at 400 MHz**
- Time stamp
- Amplitude from time-over-threshold

**HG in p.e** + **LG in p.e** + **ToF in p.e** → **Charge in p.e**
Cube response to MIP

2 GeV Muons

- Cube LY from horizontal and vertical fibers. Example
- Average LY ~ 50 p.e (for MPPC type I)

<table>
<thead>
<tr>
<th>MPPC type</th>
<th>Fiber length [cm]</th>
<th>Mean [pe]</th>
<th>Sigma</th>
</tr>
</thead>
<tbody>
<tr>
<td>I</td>
<td>24</td>
<td>51.3</td>
<td>5.9</td>
</tr>
<tr>
<td>II</td>
<td>8</td>
<td>50.2</td>
<td>8.0</td>
</tr>
<tr>
<td>III</td>
<td>8</td>
<td>47.4</td>
<td>9.3</td>
</tr>
<tr>
<td></td>
<td>8</td>
<td>38.0</td>
<td>10</td>
</tr>
</tbody>
</table>
Stopping Protons 0.8 GeV

Distribution of Energy Deposited in the stopping cube (1063 Events)

Sum of energy taken by both sets of fibers.
Time resolution

× Event median hit time is used as reference time
× Time resolution ~ 1.5 ns
  × Sample: $10^5$ muon events
  × Hits with charge > 20 p.e
  × Walk time correction is not applied

--> a lower time resolution with walk time correction is expected.
Summary

- An upgrade of the T2K near detector suite is underway to strengthen T2K physics potential
- A novel 3D plastic scintillator detector called Super FGD is under development to serve as an active target
- There are many challenges ahead to realize this detector
- Various prototyping and validation tests are on the way
- A 48x24x8 prototype was tested at CERN beam test; Results are promising

...Still much to do

- Installation of final detectors foreseen at J-PARC for summer 2021.
Back up
Alternative assembly procedure

Techniques

Ultrasonic welding on a sheet

Polystyrene sheet

- PLAPAPER (TAMIYA INC.)
  - Thickness: 0.2 mm
  - Size: 257 mm x 364 mm
  - Low cost: ~100 Yen/sheet
  - Holes can be easily made

Welding (No glue!!)

- Fabrication to join thermoplastics (or metal) by melting parts together
  → Good joint strength w/o additional variation

Ultrasonic welding

- Technique to apply ultrasonic vibration for jointing workpieces by welding
  → Good precision with less denatured at low T

Total 2688 sheets (192/24 x 192/32 x 56)
- Readout from Front face, Top face and half of Right and Left faces.
- Flat cables connect MPPC PCB to the Patch Panel
- The Patch panel and FEB towers located on two sides of the Super FGD