NUPRISM: REDUCING NEUTRINO INTERACTION MODEL DEPENDENCE FOR OSCILLATION EXPERIMENTS
T2K (TOKAI TO KAMIOKA) EXPERIMENT

See talk by T. Lindner
T2K Phase-II will be sensitive to maximal CP violation at the $3\sigma$ level.

Hyper-K will be sensitive at $5\sigma$ over a range of values of $\delta_{CP}$.

Future long baseline experiments will be limited by systematic rather than statistical uncertainties.
MEASURING NEUTRINO ENERGY

- Multi-nucleon effects.
  - Hadronic state not reconstructed.
  - Must assume mass of recoiling hadrons.
  - Problematic due to multi-nucleon interactions.
  - Explains larger axial mass preferred by MiniBooNE over NOMAD.
- Further missing hadronic energy from unseen pions.
- Both effects lead to energy underestimation.
- Many different multi-nucleon models - hard to separate experimentally.
- Energy loss different for neutrinos and anti-neutrinos.
THE NUPRISM EXPERIMENT

- An intermediate water Cherenkov detector.
  - Same nuclear target and acceptance as the far detector.
  - Smaller near to far extrapolation systematic.
- 50 m tall and 1 km downstream of neutrino beam.
  - Detector moves through cylindrical chamber.
  - Inner detector: 8 m diameter, 10 m tall.
  - Outer detector: 10 m diameter, 14 m tall.
  - Tank is lined with multi-PMT (mPMT) modules.
  - Spans 1-4 degrees from the neutrino beam axis.
  - Probes neutrino energy vs final state kinematics relationship.
  - Gd loading to measure neutron production.
NUPRISM CONCEPT
Take linear combinations of different 60 different off-axis angle slices.

\[
F(E_\nu) = \sum_{i=1}^{N_{OA}} c_i \Phi_{\nu_P,\nu}(E_\nu)
\]
- Create a neutrino flux of interest e.g. Gaussian.
- Sum the observed events to give the expected event rate.
  \[ N^F(p_\mu, \theta_\mu | E_\nu) = \sum_{i=1}^{N_{OA}} c_i N_{\nu_\mu,i}^P(p_\mu, \theta_\mu | E_\nu) \]
- Helps to constrain neutrino cross-section models.
Simulated reconstructed energy distribution for single muon candidates after applying the 1.2 GeV linear coefficients.

Separation of QE and non-QE (including multi-nucleon) scatters.

- Directly predict the effect of non-QE scatters in oscillation measurements and provide a unique constraint on nuclear models.

Cross-sections as function of true neutrino energy.

- Measure vs true observables $Q^2$ and $\omega$ - variables controlling interaction mode.
Instead of monochromatic beams, use a linear combination to produce an oscillated flux.

\[
\Phi_{SKP_{\nu_\mu\rightarrow\nu_\mu}}(E_\nu; \theta_{23}, \Delta m^2_{32}) = \sum_i c_i(\theta_{23}, \Delta m^2_{32}) \Phi_i^{\nu P}(E_\nu)
\]

Can reproduce oscillated flux between \(~400\, \text{MeV} \) and \(1.2\, \text{GeV}\).

Directly measure muon \(p\)-theta for given oscillation parameters.

For each oscillation hypothesis we want to test, we find a linear combination of the NuPRISM off-axis fluxes to give the oscillated spectrum.
Red: Directly measured NuPRISM events in far detector prediction.

Green: Non-CC0π background subtracted at NuPRISM and re-added at SK with significant cancellation.

With matched fluxes:

- NuPRISM linear combination event rate the same as oscillated SK event rate.
- Directly compare NuPRISM measurement to observed SK events to obtain oscillation parameters.

NuPRISM and SK have the same interaction material - same interaction cross-section.

No cross-section model, no effect from wrong model choice.
Instrumented portion of phase 1 is placed in a water tank near ND280.

Allows us to demonstrate detector/calibration precision.

Provides a test detector for Hyper-K R&D.

Physics goals:

- Measure $\sigma(\nu_e)/\sigma(\nu_\mu)$ to $\sim3\%$ precision.

- Expect $\sim5500 \nu_e$ events below 1 GeV in $1 \times 10^{21}$ POT with 76\% purity.

- Gd loading to measure neutron multiplicities in neutrino-nucleus interactions.

A range of locations being studied.

- Optimise flux uncertainties and flux ratios.

- Investigating feasibility of construction.
MULTI-PMT (MPMT) R&D

- Modular approach to PMT instrumentation.
  - Array of small (~3") PMTs rather than one large one.
  - Waterproofing, pressure protection, reduced cabling.
  - Readout electronics, monitoring, calibration devices located in vessel.
  - Directional information - improved vertex resolution.
- Leveraging lessons learned from KM3NeT/IceCube mPMT design.
- Mechanical design (TRIUMF, Toronto).
- Optical characterisation of PMTs, acrylic, etc. (Toronto, York, Alberta, TRIUMF).
- Electronics development (TRIUMF, Warsaw UT, Michigan State).
- Ongoing studies of support structure, acrylic vessel engineering, reflector assembly, optical gel, etc.
J-PARC PAC Stage 1 status granted in July, 2016.


First chance for full approval at the January 2018 PAC meeting.

Plan to take 2 years of Phase 0 data starting 2021.
  - Phase 0 start driven by mPMT development and construction.

Aim to take Phase 1 data ~3 years after Phase 0 start.
  - Data taking for last 2-3 years of T2K-II run.
CURRENT T2K SYSTEMATIC ERRORS

- Systematic uncertainty at the 6% level. Need reduction to ~3% level for Hyper-K.

<table>
<thead>
<tr>
<th>Source of uncertainty</th>
<th>( \mu )-like ( \delta \left( \frac{#\nu\text{-mode}}{#\bar{\nu}\text{-mode}} \right) / \left\langle \frac{#\nu\text{-mode}}{#\bar{\nu}\text{-mode}} \right\rangle )</th>
<th>( e )-like ( \delta \left( \frac{#\nu\text{-mode}}{#\bar{\nu}\text{-mode}} \right) / \left\langle \frac{#\nu\text{-mode}}{#\bar{\nu}\text{-mode}} \right\rangle )</th>
</tr>
</thead>
<tbody>
<tr>
<td>SKDet</td>
<td>0.07%</td>
<td>1.6%</td>
</tr>
<tr>
<td>FSI+SI</td>
<td>2.6%</td>
<td><strong>3.6%</strong></td>
</tr>
<tr>
<td>Flux</td>
<td>1.8%</td>
<td><strong>1.8%</strong></td>
</tr>
<tr>
<td>Flux+XSec (ND280 constrained)</td>
<td>1.9%</td>
<td><strong>2.2%</strong></td>
</tr>
<tr>
<td>XSec NC other (uncorr)</td>
<td>0.0%</td>
<td>0.2%</td>
</tr>
<tr>
<td>XSec NC 1( \gamma ) (uncorr)</td>
<td>0.0%</td>
<td>1.5%</td>
</tr>
<tr>
<td>XSec ( \nu_e / \nu_\mu ) (uncorr)</td>
<td>0.0%</td>
<td><strong>3.1%</strong></td>
</tr>
<tr>
<td>Flux+XSec</td>
<td>1.9%</td>
<td>4.1%</td>
</tr>
<tr>
<td><strong>All</strong></td>
<td><strong>3.2%</strong></td>
<td><strong>5.8%</strong></td>
</tr>
</tbody>
</table>

- CP violation measurement depends on uncertainty of \( \nu_e/\bar{\nu}_e \) ratio.

- Dominant uncertainties:
  - **Final state interactions (FSI) and secondary interactions (SI)** - nuclear model extrapolated from pion-nucleus scattering experiments.
  - **Electron/muon neutrino cross-section ratio** - need data in energy range of interest, low statistics and large background for electron samples.
  - **ND280 flux + cross-section constraint** - affected by nuclear model uncertainties.
MULTI-NUCLEON MODELS

Many different theoretical models.

Martini et al. and Nieves et al. calculations are both consistent with MiniBooNE data within the MiniBooNE flux uncertainties.

The np-nh contributions can differ by a factor of 2 in the region of interest.

Predict different rates for neutrinos vs anti-neutrinos.

Hard to separate models experimentally.
Oscillations result in different fluxes at the near and far detectors.

- Causes issues constraining interaction model that predicts far detector event rates.

Detectors measure convolution of neutrino flux with interaction model.

- Measurement of near detector does not directly constrain far detector event rate.

- Smearing of neutrino energy a relatively small effect at the near detector but significantly impacts measurement of oscillation parameters.

- Different acceptances causes further issues.
EFFECT OF MULTI-NUCLEON CROSS-SECTION MODELLING

- T2K study of $\sin^2 \theta_{23}$ uncertainty from mis-modelling the 2p-2h part of the cross-section found a significant bias and uncertainty.

- Same study is carried out using NuPRISM near detector fit.

- SK event rate is accurately predicted even with additional 2p-2h interactions added to the toy data.

- The $\sin^2 \theta_{23}$ bias and uncertainty are reduced to ~1% with the NuPRISM measurement.

- NuPRISM analysis largely independent of cross-section model.