Study of neutrons associated with neutrino interactions in water with the IWCD detector

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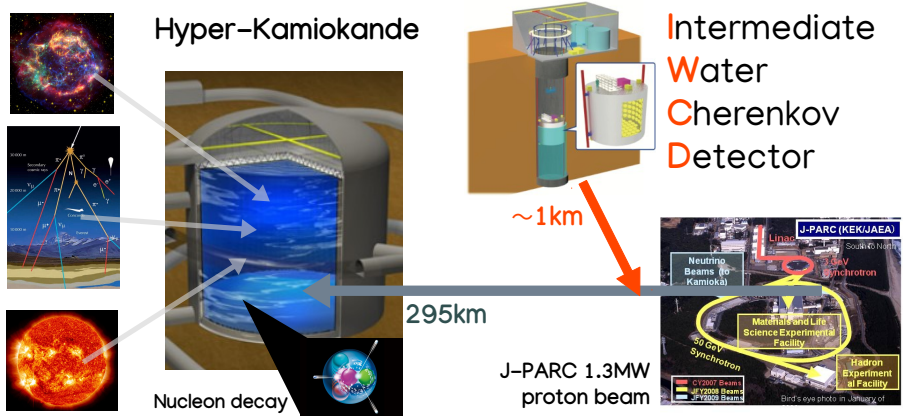
for the Hyper-Kamiokande collaboration

June 10, 2021/2021 CAP Virtual Congress

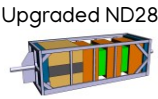
TRIUMF



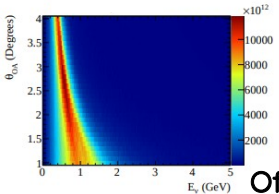
- Long-baseline neutrino oscillation program, following the successful T2K experiment
  - 2.5× more intense beam and 8× larger fiducial mass than Super-Kamiokande's one
- 20× of T2K's event rates → more important to predict event rates accurately

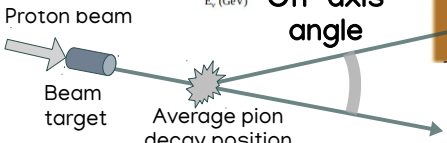
IWCD

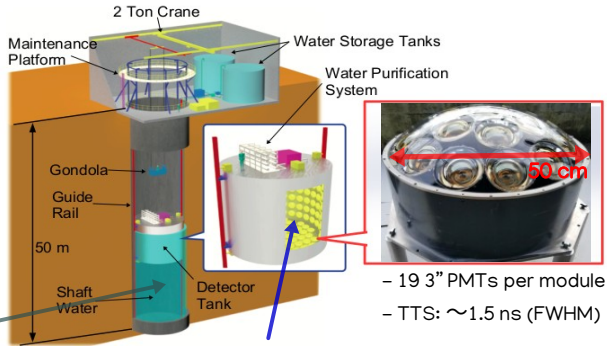
- Sub-kiloton scale Water Cherenkov detector
  - One of near detectors for Hyper-Kamiokande
  - Located at about 1km from neutrino production point
  - New photo sensor modules
  - Loading with Gd for neutron detection
  - Vertically movable



Other near detectors



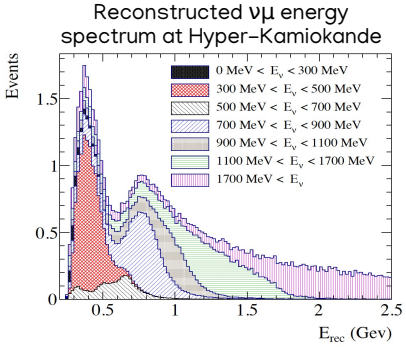




- 19 3" PMTs per module
- TTS: ~1.5 ns (FWHM)

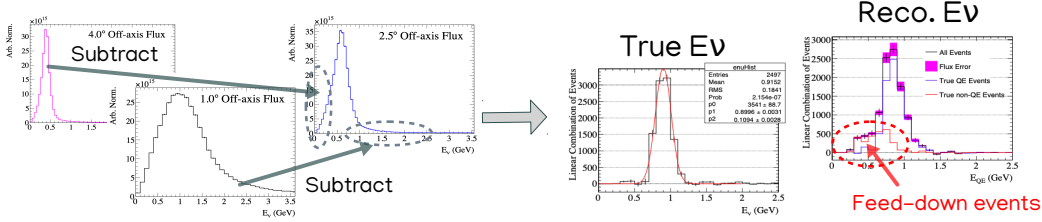
Inner detector size
- 8m diameter
- 6m height

IWCD's measurement programs (1/2)



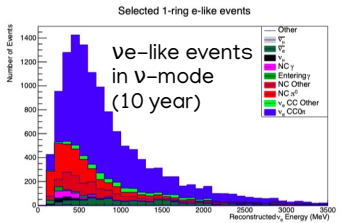
◆ Measurement of true-reco. ν energy mapping for ν mixing angle θ_{23} measurement

- Charged-Current Quasi Elastic (CCQE) reaction is assumed for ν energy reconstruction
- Non-CCQE interactions tend to be reconstructed as low-energy events (feed-down events)
- Taking data at different off-axis angles enables studying relation between true and reco. energies

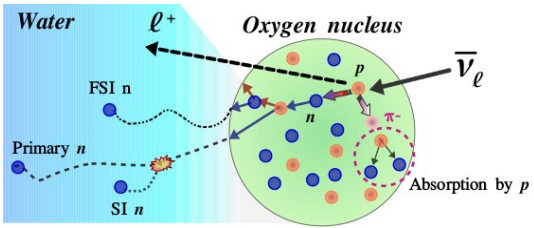


IWCD's measurement programs (2/2)

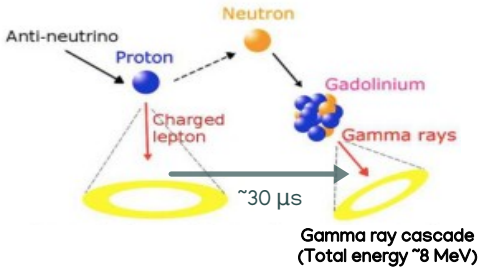
- Measurement of νe($\bar{\nu}$e) cross section for leptonic CP violation search
  - Need to predict νe($\bar{\nu}$e) event rate accurately
  - νe($\bar{\nu}$e) exist as 1% contamination in νμ($\bar{\nu}$μ) beam
  - Will measure the double-cross section ratio $\frac{\sigma(\nu_e)/\sigma(\nu_\mu)}{\sigma(\bar{\nu}_e)/\sigma(\bar{\nu}_\mu)}$



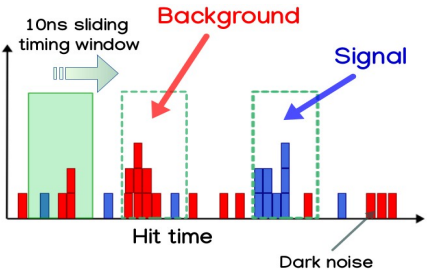
- Measurement of neutron multiplicities
  - Many analyses at Hyper-Kamiokande will utilize information about tagged neutrons
    - Nucleon decay searches
    - Supernova relic neutrino searches
    - Neutrino oscillation measurements
  - Large uncertainties on neutron multiplicities due to complicated production processes
  - Need to constrain the multiplicities by data

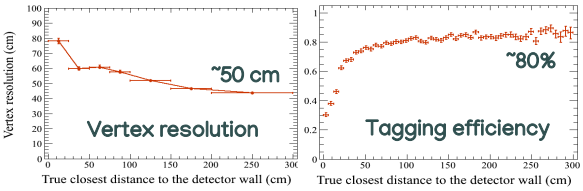


Simple neutron reconstruction



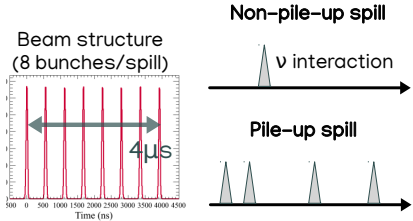
- Searching for neutron signals up to +100μs after signal ν interactions
- Identifying clustered PMT signals in time as neutron candidates
- Reconstructing neutron capture vertex
  - Finding the position that minimizes TOF subtracted timing of PMT signals
    - TOF: time-of-flight of photon creating PMT signal

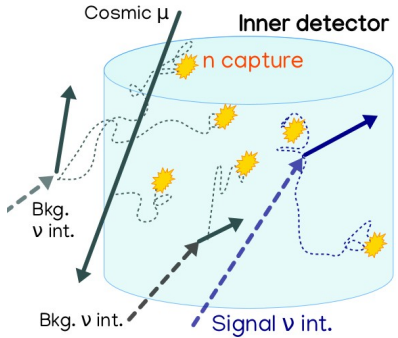




Neutron measurement with event pile-up effect

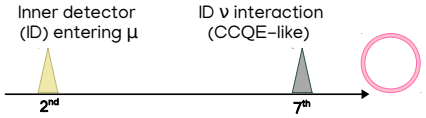
- There will be event pile-up
  - Multiple neutrino interactions per spill
- Neutrons from background neutrino interactions could be serious issue
- Studied feasibility of neutron measurement with event pile-up
  - Statistics
  - Efficiency
  - Purity

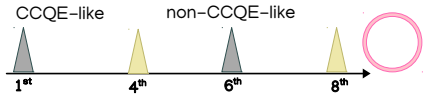


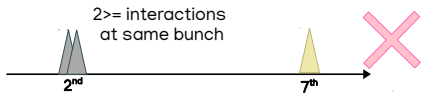


Simulation & Analysis

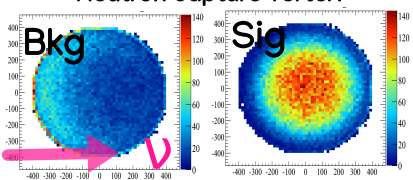
- **Simulations**
  - Simulating single events
    - `NEUT` for ν interactions
    - `CRY` for cosmic shower particles
    - `Geant4` for propagating particles from `NEUT` & `CRY` through IWCD's geometry
  - Making pile-up spills
    - Combining single events with one spill, considering event rates and event timing
- **Analyses**
  - Selecting "clean" spills (top right drawings)
    - Signal ν interactions: CCQE-like
  - Apply vertex cuts to neutron capture candidates



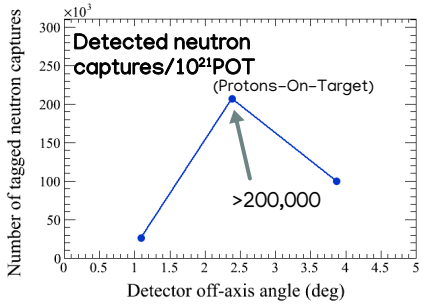


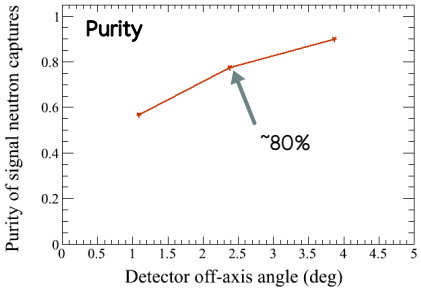


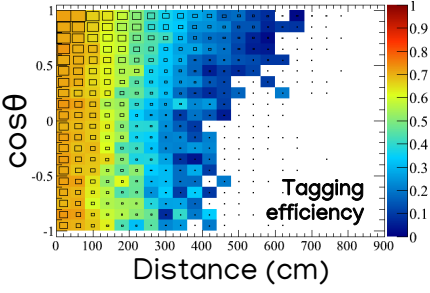
Neutron capture vertex

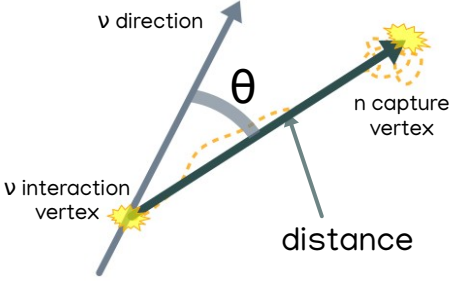


Results


Detected neutron captures/10²¹POT
(Protons-On-Target)
>200,000
Number of tagged neutron captures
Detector off-axis angle (deg)


Purity
~80%
Purity of signal neutron captures
Detector off-axis angle (deg)


Tagging efficiency
cosθ
Distance (cm)


ν direction
θ
n capture vertex
ν interaction vertex
distance

Summary

- The Intermediate Water Cherenkov Detector (IWCD) is planned as one of the near detectors for the Hyper-Kamiokande's long-baseline neutrino oscillation program
- The IWCD's measurements of neutrino interaction rates are important to control systematic uncertainties for the program
- The IWCD detector is also planed to be operated with Gd sulfate loading, in order to enhance ability of neutron detection
- Feasibility of neutron multiplicity measurements with event pile-up was evaluated
- With simple neutron reconstruction, IWCD will be able to collect high statistics of detected neutron candidates with high purity and high detection efficiency