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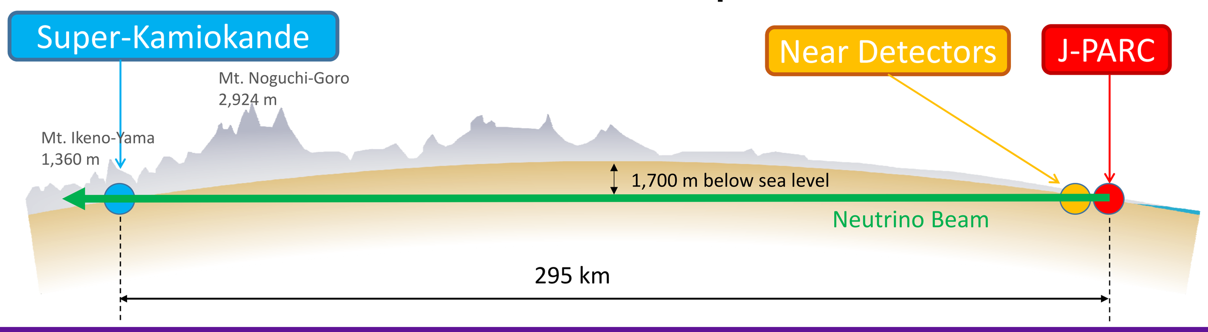
A Study of Applications of Neutron Capture Signal for the T2K Experiment

Seidai Tairafune for the T2K collaboration
(Tohoku University)

1. T2K Experiment

- A long-baseline neutrino oscillation experiment.
- Measure neutrino oscillation parameters, and search for CP violation in the leptonic sector.



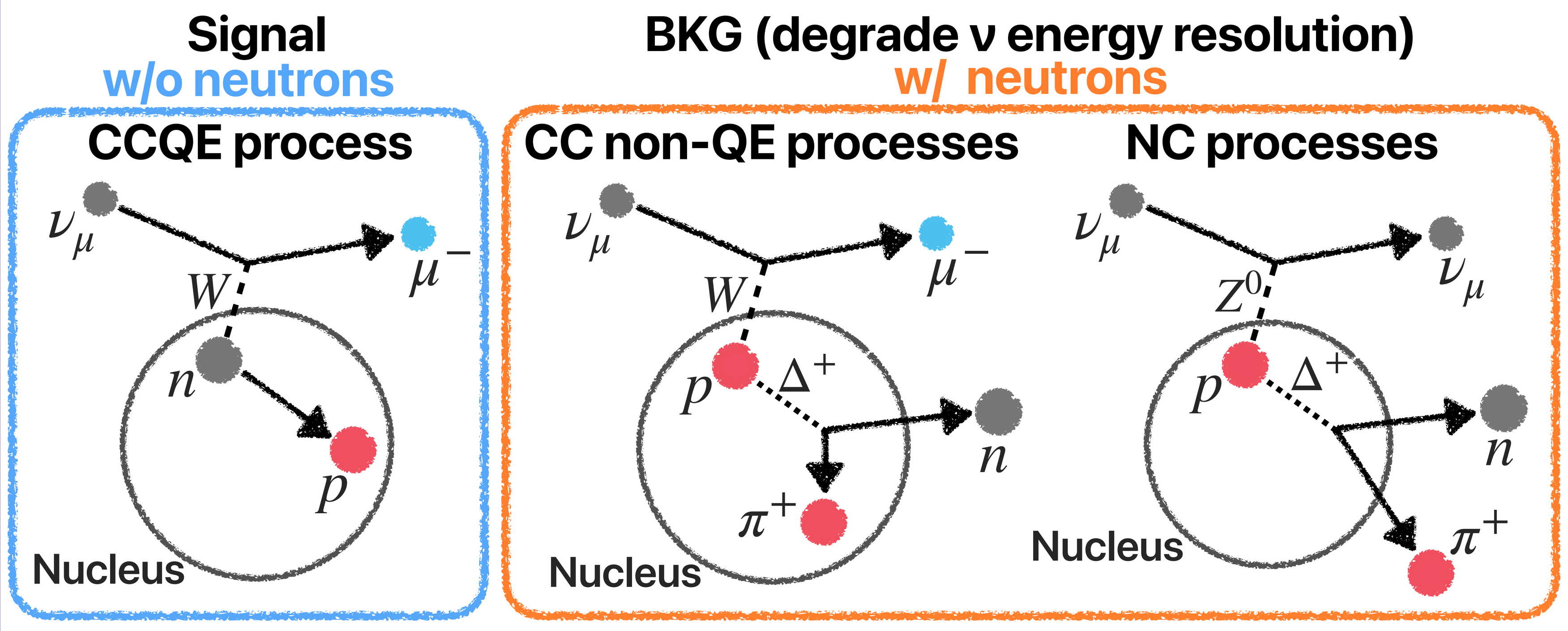
Oscillation probability ($\nu_\mu \to \nu_\mu$ disappearance mode)

$$P(\nu_\mu \to \nu_\mu) \sim 1 - \left(\cos^4\theta_{13}\sin^2 2\theta_{23} + \sin^2 2\theta_{13}\sin^2\theta_{23}\right)\sin^2\left(\frac{1.27\Delta m^2_{32} L}{E_\nu}\right)$$

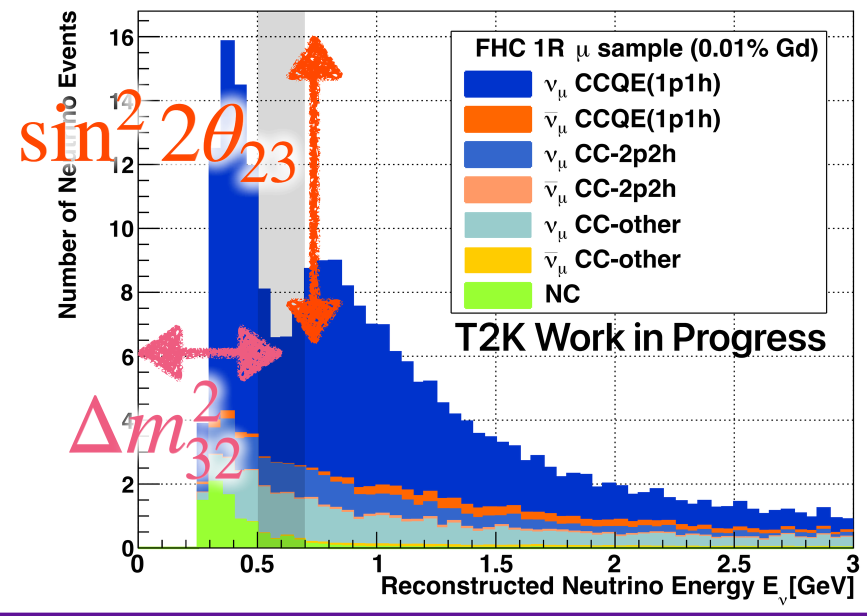
L : Length of flight [km]
E_ν : Energy of neutrino [GeV]
θ_{ij} : Mixing angles
Δm^2_{ij} : The mass squared differences [eV²]

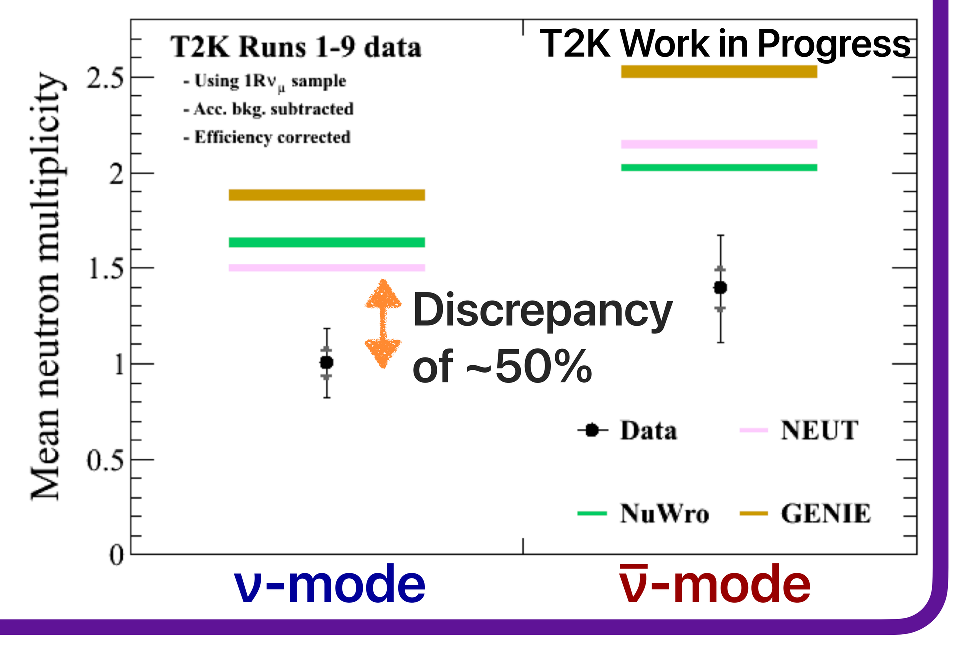
2. Application of Neutron Signal at T2K

- Neutron multiplicity gives information of interaction type.



- **Sensitivity for θ_{23} and $|\Delta m^2_{32}|$** would be improved by separating ν interactions.
- **Large uncertainty of neutron multiplicity in hadronic final-state-interaction(FSI) and secondary interaction(SI) in the detector medium**[1] is one of the critical issues for neutron application in neutrino physics.





3. Purposes of This Study

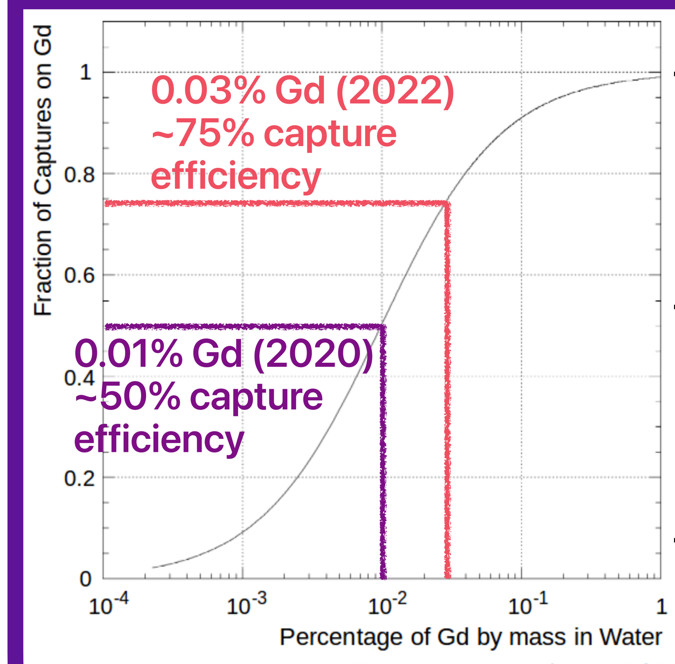
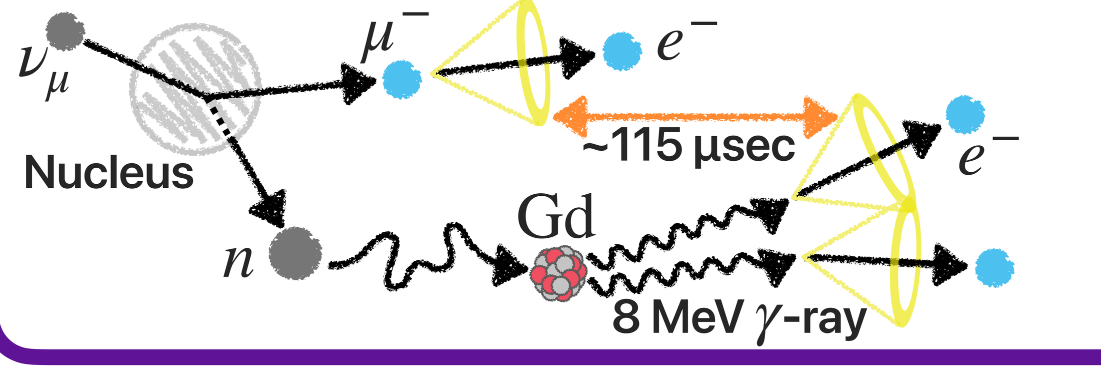


Figure taken from [2]

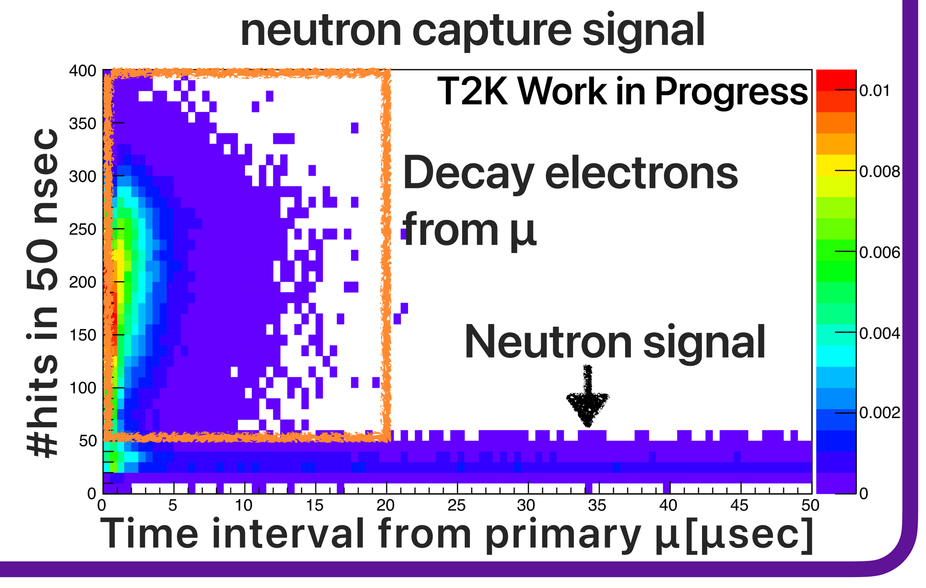
- Gd is loaded into the Super-Kamiokande detector, and high efficiency neutron tagging is now available.
- **Estimate sensitivity improvements from the separation of ν interactions via neutron.**
- **Understand the systematic error on the mean neutron multiplicity.**

4. Primary Selection

- Focus on **1-ring μ-like sample**.
- Neutron capture signal is a delayed signal, and it can be mimicked by a decay electron.
- Efficiency of ν events from fully-contained fiducial volume cut is ~60%.

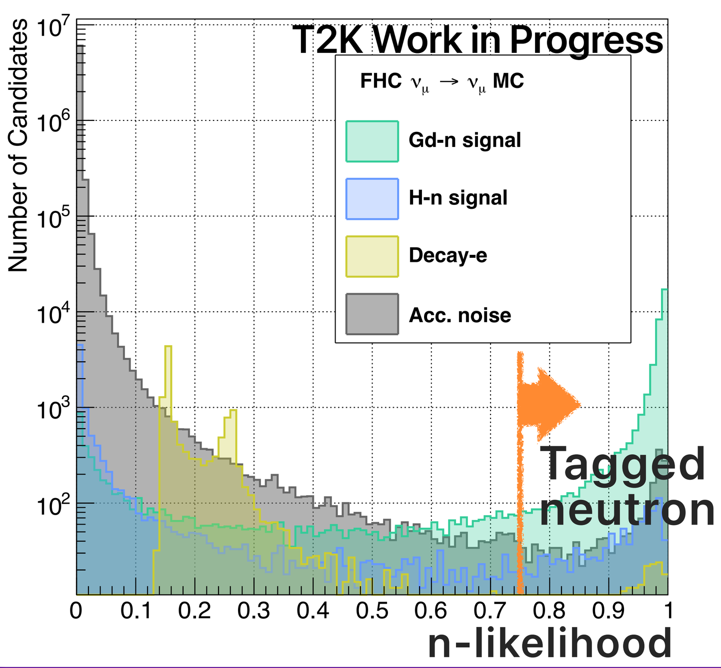


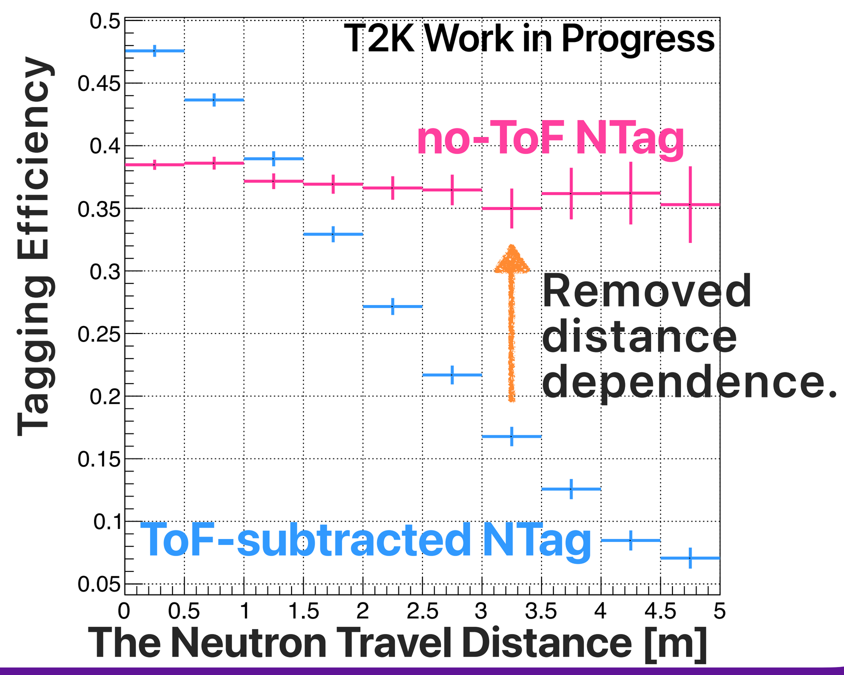
Separation of decay electrons and neutron capture signal



5. Neutron Tagging Algorithm

- There are two steps for neutron tagging(NTag):
  1. **Pre-selection**
     - Search PMT hit clusters.
       The past NTag used ToF-subtracted hit time for proton-captured neutrons. In this analysis, use raw PMT hit time to avoid large bias of neutron flight distance from n-nucleus interaction model.
       (ToF = time of flight between the primary vertex and PMT)
  2. **Neural network(NN) classification**
     - Use 12 input variables:
       # of hits, angular or isotropic variables to separate neutron signal from accidental noise.



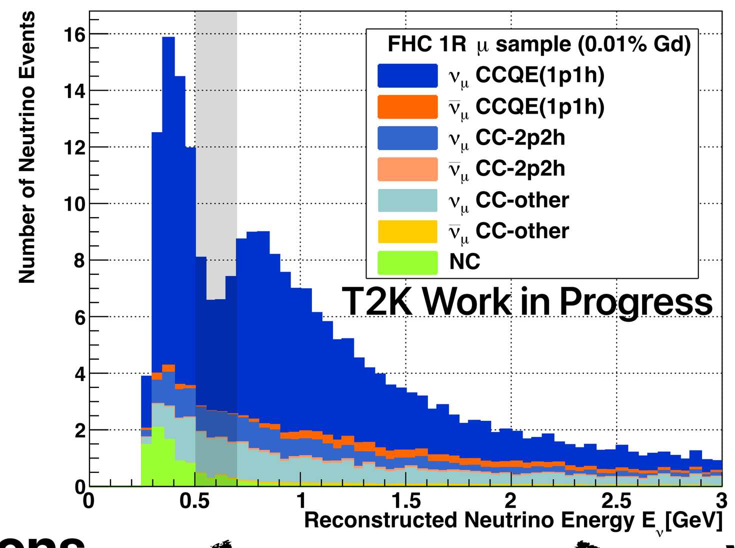


6. Separation of ν Interactions via Neutrons

- Separate 1-ring μ-like sample according to the number of tagged neutrons.
- Estimate composition of each sample in term of interaction processes.

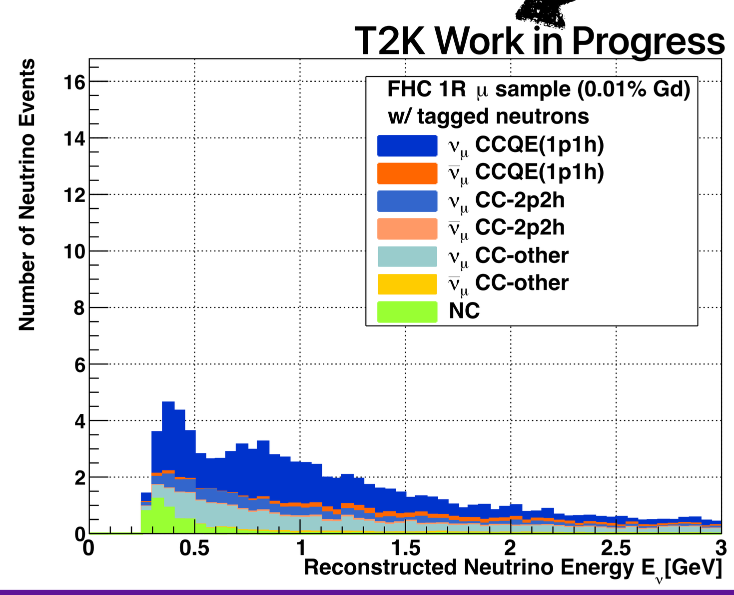
	CCQE	CC non-QE	NC
No NTag	72.0%	23.3%	4.6%
w/ neutron	56.2%	36.0%	7.8%
w/o neutron	80.6%	16.5%	2.9%

T2K Work in Progress

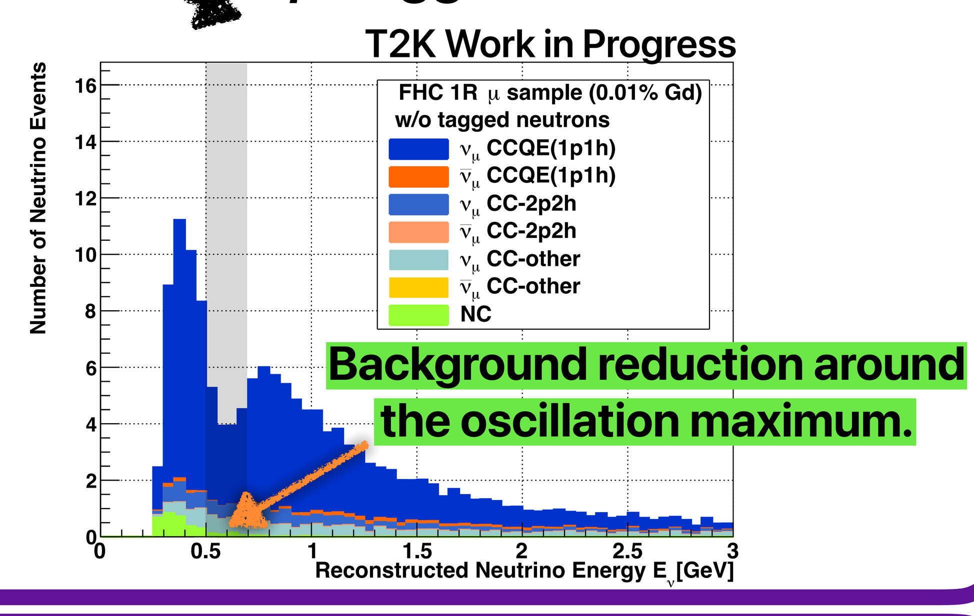


ν-mode 1-ring μ-like sample with 0.01% Gd concentration

w/ tagged neutrons



w/o tagged neutrons



7. Summary

- Applications of high efficient neutron detection can improve oscillation analysis at T2K.
- Separation performance of ν interactions via tagged neutrons was estimated, and the purity of CCQE was improved in 1-ring μ-like sample without neutrons.
- Estimation of NTag impacts on oscillation analysis is ongoing.
- Measurement and understanding of neutron multiplicity with Gd data are also essential for utilizing neutron information in neutrino experiments.

[1] R. Akutsu, "A Study of Neutrons Associated with Neutrino and AntiNeutrino Interactions on the Water Target at the T2K Far Detector", PhD. thesis (2019)
[2] Ll. Marti, et. al., "Evaluation of Gadolinium's Action on Water Cherenkov Detector Systems with EGADS" (2020)