Neutron Tagging Efficiency Evaluation in the Super-Kamiokande Gd Phases

#102

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① Super-Kamiokande (SK-Gd)

- Water-Cherenkov neutrino detector with the fiducial volume of 22.5k tons.
- To improve sensitivity of Diffuse Supernova Neutrino Background(DSNB)[1], gadolinium(Gd) was added to the target volume, former ultra-pure water.

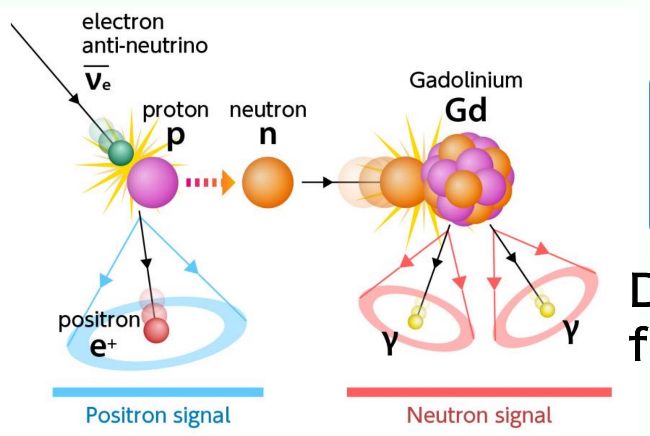
July 2020~ Gd 0.011wt%[2]
June 2022~ Gd 0.033wt%[3]
Latest search : see poster #360

◻ DSNB, Reactor neutrino

Identify inverse beta decay(IBD) events

$\bar{\nu}_e + p \rightarrow e^+ + n$

via delayed coincidence of e^+ and n signals.



Search with Neutron tagging (Ntag)[4] algorithm

Distinguishing $\bar{\nu}_e$ events from BG events

Other physics with neutron detection

◻ Atmospheric neutrino

Using neutron multiplicity distributions,
- Improve energy reconstruction with neutrons[5].
- Classify interaction channels.

⇨ Improve precision of oscillation analysis.

◻ Supernova neutrino

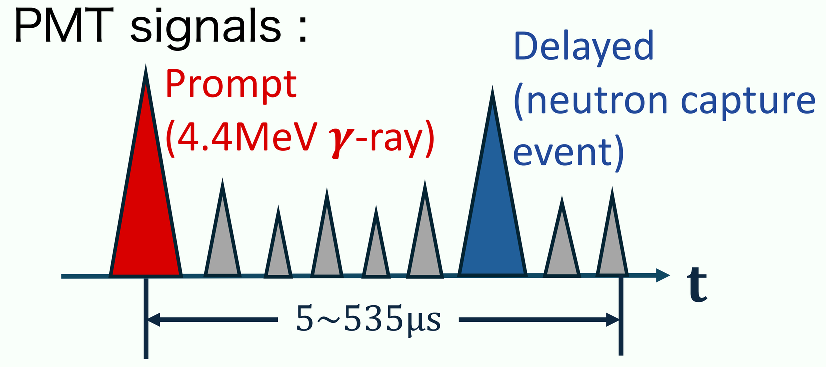
- Identify IBD events and separate from ES events.

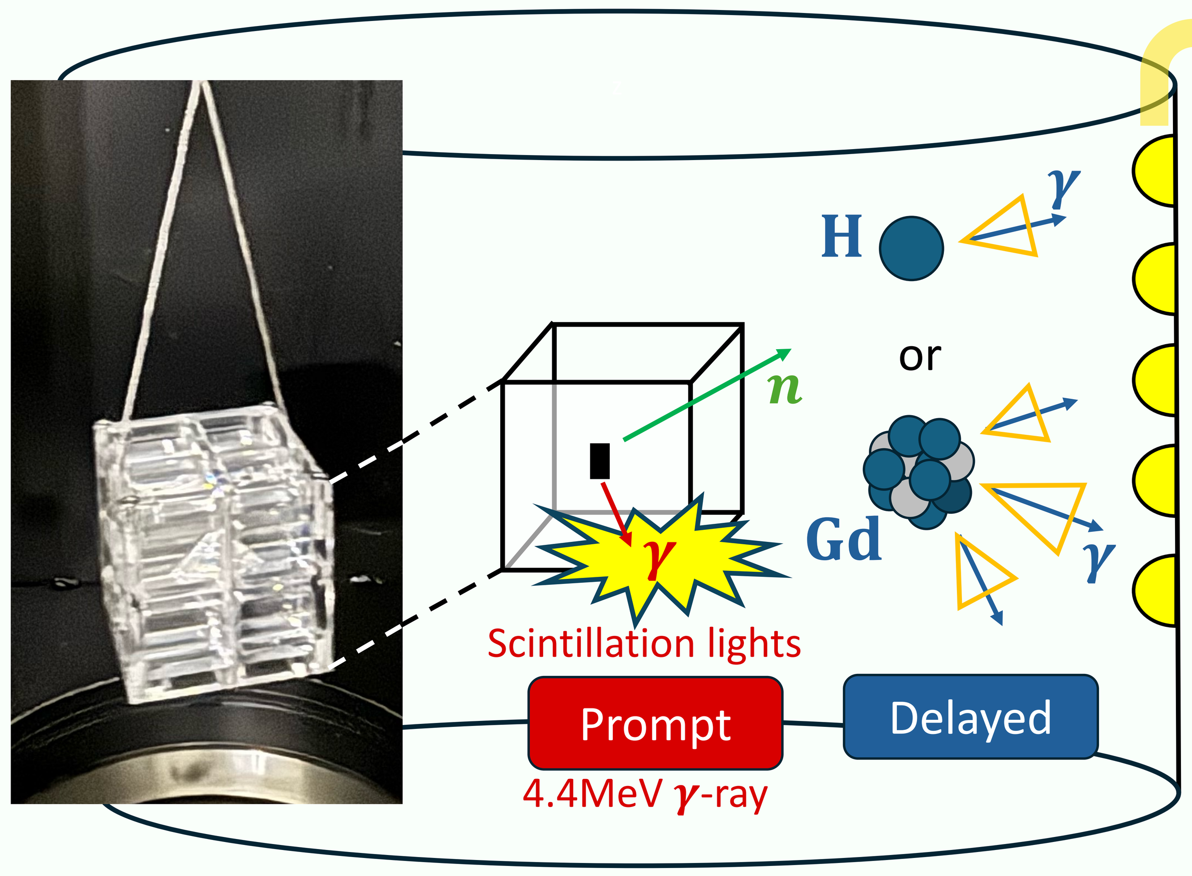
⇨ Improve supernova pointing accuracy.

② Calibration using ^{241}Am-Be

It is important to calibrate the neutron detection efficiency and guarantee stable performance, for our precision physics analysis.

Calibration source : ^{241}Am-Be(Am/Be) surrounded BGO crystals





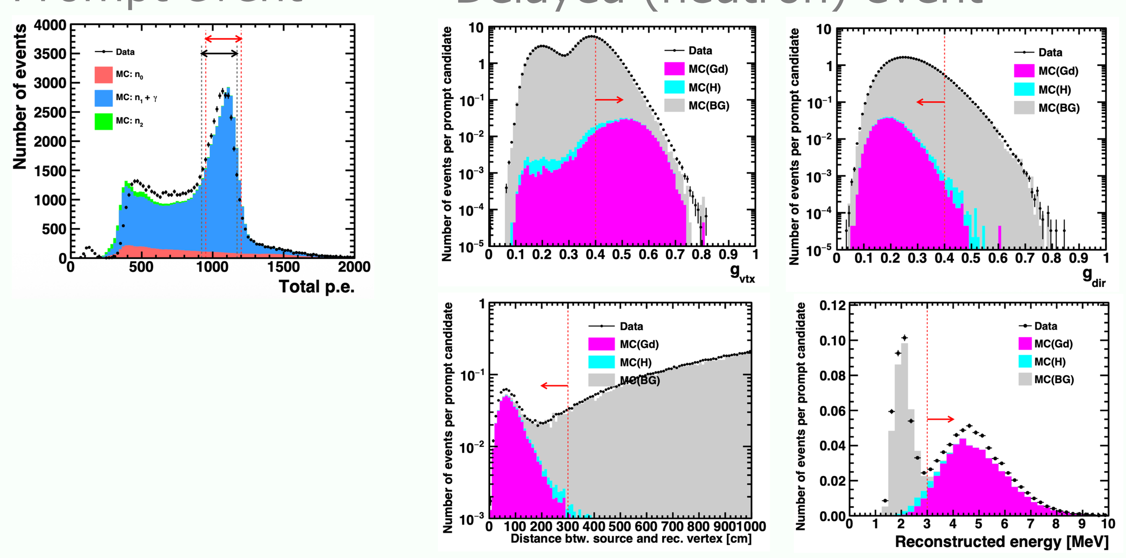
- ◻ Event reconstruction is performed to the Gd(n,γ) event candidates, and then event selection cuts are applied (box-cut method[6]).
- ◻ The comparison of neutron detection efficiency (Ntag efficiency) between calibration data and MC simulation is performed, both to understand the data and to evaluate the systematic uncertainty of our detector simulation.

$$\text{Ntag efficiency} = \frac{\text{Number of delayed events}}{\text{Number of prompt events}}$$

- ◻ Compared with Neural Network (NN) method, box-cut method enables parameter-by-parameter systematic uncertainty evaluation using well-understood physical parameters.

Event selection (box-cut method)

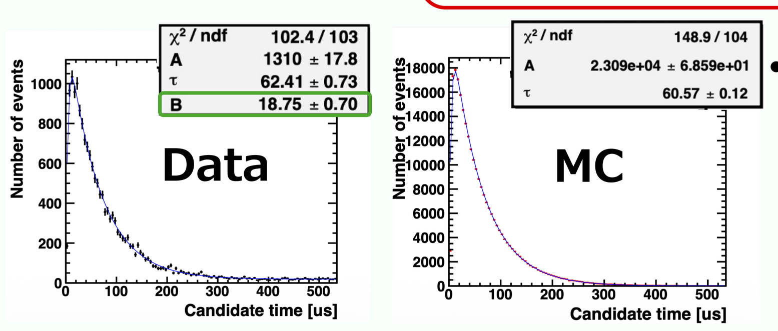
Prompt event   Delayed (neutron) event



Prompt-Delayed time difference

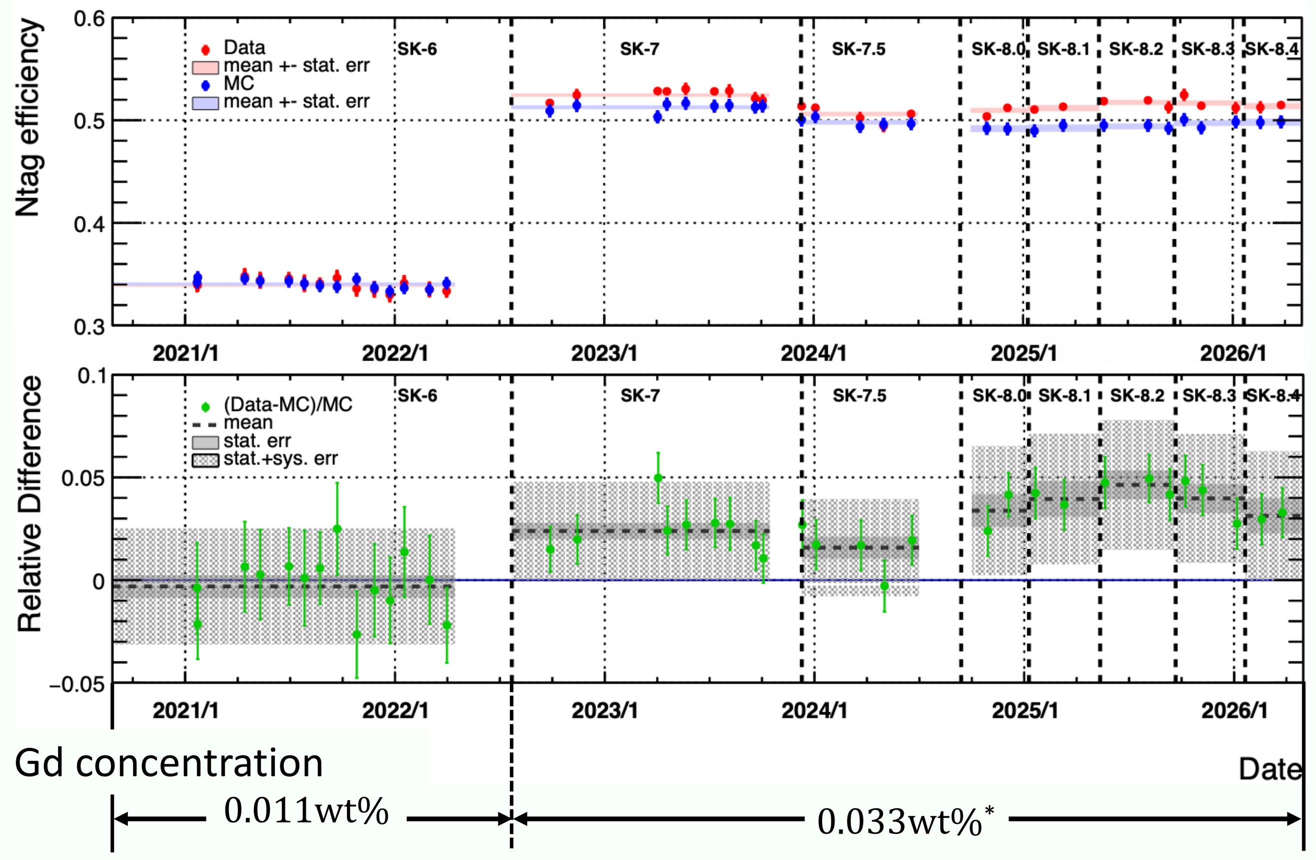
$$f(t) = A\exp\left(-\frac{t}{\tau}\right)\left[1-\exp\left(-\frac{t}{\mu}\right)\right] + B$$

τ : Neutron Capture Time Constant
μ = 4.3μs : Thermalization Time Constant (measured)
BG events



Only Calibration data contain accidental background events (B component).

③ Time Variation of Neutron Detection Efficiency



Ntag efficiency was calculated using the Am/Be calibration data taken at the detector center position.

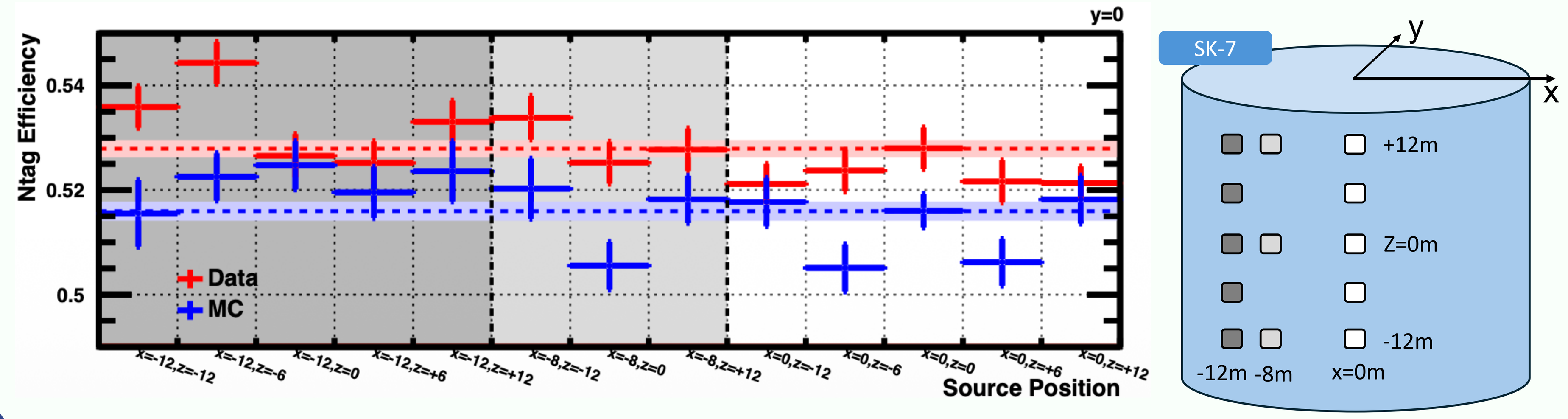
- Ntag efficiency is stable along SK-Gd phases, especially SK-7.5, where we have different condition of geomagnetic compensation coils.
- The Am/Be calibration data is well reproduced with MC, almost within the expected uncertainty.
- Data still show a relative 3~4% excess in Ntag efficiency compared to MC during the 0.033wt% Gd period.

*(Geomagnetic compensation coil conditions differ between each phase.)

Representative value

Ntag eff.	SK-6	SK-7	SK-7.5	SK-8.0	SK-8.1	SK-8.2	SK-8.3	SK-8.4
Data[%]	34.0±0.1(stat.)	52.5±0.1(stat.)	50.6±0.2(stat.)	51.0±0.2(stat.)	51.2±0.3(stat.)	51.7±0.2(stat.)	51.7±0.2(stat.)	51.4±0.3(stat.)
MC [%]	34.1±0.1(stat.) ±0.9(sys.)	51.3±0.1(stat.) ±1.2(sys.)	49.8±0.2(stat.) ±1.1(sys.)	49.2±0.3(stat.) ±1.4(sys.)	49.2±0.3(stat.) ±1.4(sys.)	49.4±0.3(stat.) ±1.5(sys.)	49.7±0.3(stat.) ±1.5(sys.)	49.8±0.3(stat.) ±1.5(sys.)

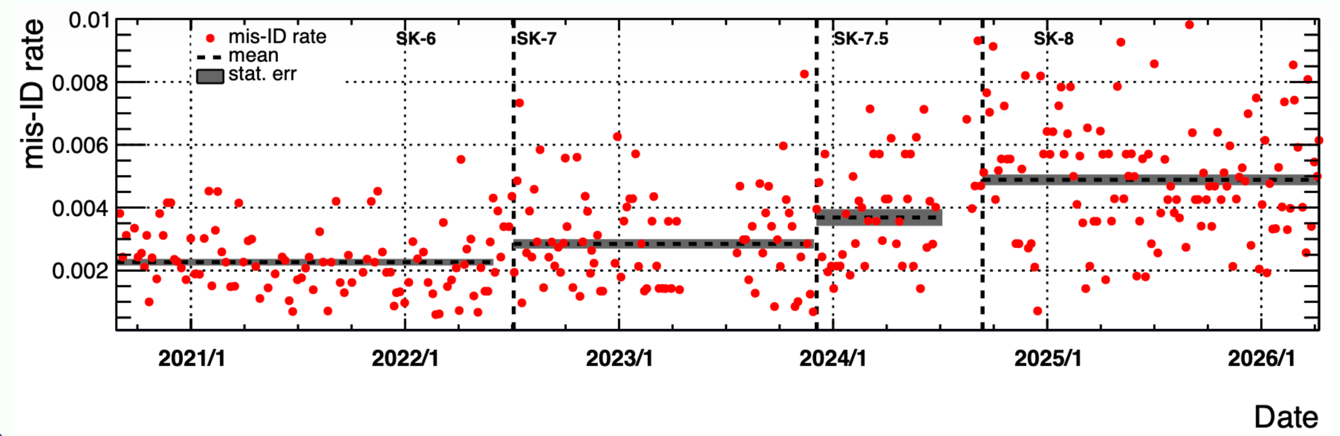
④ Detector Position Dependence of Ntag efficiency



This position dependence is included in the systematic uncertainty estimation.

- Data and MC agree within a relative difference of ~2% throughout the detector volume.

⑤ Time Variation of Misidentification rate (mis-ID rate)



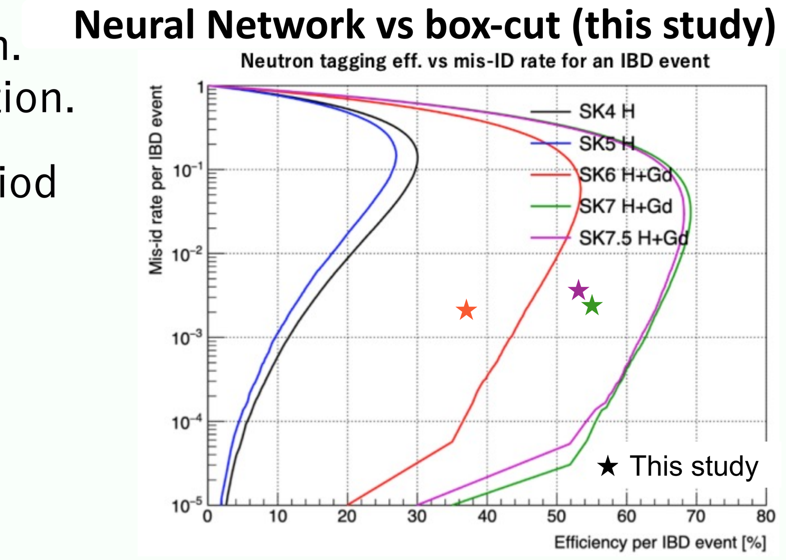
Mis-ID rate :
Fraction of events, in which neutron candidates are found in spite of no Am/Be source.

- The average mis-ID rate is ~10^{-3}.
- The increase in SK-7.5, 8 is due to detector condition, possibly PMT dark-noise rate or water quality.

⑥ Summary and Implications for DSNB Analysis

- Neuron tagging with Gd is the key technology of Super-Kamiokande Gd, for DSNB search. This study confirmed the stable efficiency of neutron tagging with Am/Be source calibration.
- MC reproduces the representative Ntag efficiency of calibration data for each SK-Gd period and also reproduces the variation across periods.
- Ntag misidentification rate remained at the 10^{-3} level.
- Based on this research, neural network method is applied for the neutron tag of DSNB analysis. The agreement between data and MC is consistent with this study.

Neural Network vs box-cut (this study)



1. M. Harada, et al. 2023, *ApJL*, 951, L27
2. SK, Nucl. Instr. Meth. A 1027 (2022) 166248.
3. SK, Nucl. Instr. Meth. A 1065 (2024) 169480.
4. S. Han, 2024. "Measurement of neutrons produced in atmospheric neutrino interactions at Super-Kamiokande" (PhD Thesis, The University of Tokyo)
5. S. Miki, 2025. "Neutrino mass ordering determination using atmospheric neutrinos with neutron detection in Super-Kamiokande"(PhD Thesis, The University of Tokyo)
6. M. Harada, 2023. "Development of Neutron Tagging Algorithm and Search for Supernova Relic Neutrino in SK-Gd Experiment" (PhD Thesis, Okayama University)