Development of Neutron Tagging Algorithm for Hyper-Kamiokande with Pure Water

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Abstract. Neutron tagging algorithm is under development for Hyper-Kamiokande. The algorithm aims to distinguish neutron capture events from the background due to random coincidence of dark noise hits. The tagging efficiency of neutron capture events and the misidentification of the background are evaluated in the detectors with different dark rates. In this baseline design with 8.4 kHz dark rate, the tagging efficiency is found to be 54% (49%) with 10% contamination of dark noise background if the true (reconstructed) vertex position is used, while the efficiency reaches 71% if the dark rate is suppressed to 3.0 kHz.

1. Introduction
The Hyper-Kamiokande project is a plan for a future neutrino experiment with large volume water Cherenkov detector. The detector can accumulate high statistics data with approximately 20 times larger fiducial volume than Super-Kamiokande. Various physics studies are possible using Hyper-Kamiokande, such as neutrino oscillation study including CP-violation measurement, nucleon decay search, and astro-particle physics. The baseline design of the detector has been discussed and determined, while further improvement is still possible according to feedback from physics studies, including neutron tagging, and depending on R&D of the detector hardware. Neutrons are emitted in charged current (CC) quasielastic (QE) interaction of anti-neutrinos. The feature can be used to separate neutrino and anti-neutrino interaction and also used to suppress background in proton decay search. For example, one of typical background process in studies of the $p \rightarrow e^+\pi^0$ decay mode is atmospheric neutrino interaction: $\bar{\nu} + p \rightarrow n + e^+ + \pi^0$, which can be removed if the neutron is tagged. In this article, neutron tagging algorithm and its performance are described.

2. Neutron tagging algorithm
This algorithm searches for 2.2 MeV $\gamma$ signal emitted from neutron capture on hydrogen, for which only about 14 PMT hits are expected when the photocoverage is 40%. Random coincidence of dark noise can be background if such coincidence occurs within 1025 $\mu$s time window after the prompt signal (the time window is set to contain neutron capture with mean capture time of about 205 $\mu$s). The algorithm consists of following three steps. 

1. Neutron event candidate search
Create (hit time) - (time of flight) distribution and search for hit cluster in 10 ns sliding
time window. If the number of hits in 10 ns exceeds the threshold, the hit cluster is selected as neutron candidate. Time of flight in this step is calculated assuming the neutron capture vertex is the same as that of the prompt signal.

2. Vertex reconstruction
The neutron capture vertex is searched by comparing the (hit time) - (time of flight) distribution as a function of vertex position. The time distribution is fitted by an exponentially modified Gaussian function, and the position which gives the best-fit is chosen as 2.2 MeV $\gamma$ vertex in the next step.

3. Signal/Background identification based on likelihood analysis
The background reduction is done by using likelihood analysis. In order to reject the accidental background, three parameters are evaluated.

Acceptance
The incident probability of light from 2.2 MeV $\gamma$ vertex when the light emitted isotropically. This parameter includes the attenuation of light and solid angle of each PMT from the vertex. The dark noise is independent from reconstructed $\gamma$ vertex, and the acceptance of accidental background event tends to be lower than signal.

Opening angle
The mean of opening angle between direction of $\gamma$ and that from $\gamma$ vertex to PMTs with signal. This parameter is introduced to consider the effect of the directivity of Cherenkov lights.

Capture time
The time from prompt signal emission to the detection time of candidates. The neutron capture time is exponentially distributed, on the other hand, background event is uniformly distributed.

Figure 1. Example of likelihood distribution of each parameters (left: acceptance, center: opening angle, right: capture time). Solid blue line and broken red line shows signal likelihood of signal and background. (number of hits in 10 ns: 13 hits, dark rate: 8.4 kHz)

Figure 1 shows the comparison of the signal likelihood distribution between signal and background events. Threshold is set to the sum of 3 parameters’ likelihood values. When the sum of likelihood exceeds threshold, the event is regarded as 2.2 MeV $\gamma$ event. Currently, only the accidental coincidence of dark noise is considered as the background.

3. Performance Evaluation
Neutron tagging efficiencies are evaluated with the baseline design of Hyper-Kamiokande[1], which has 8.4 kHz dark rate and 40% photo-coverage, and also with different dark rates, 3.0, 4.2, and 6.0 kHz. The results are summarized in Figure 2 and Table 1. The selection criteria are set to reduce the background contamination to 10% with respect to the signal. The tagging efficiency of current baseline design with true (reconstructed) vertex position is found to be 54%
(49%). If the dark rate is suppressed to 3.0 kHz and true vertex is used, the tagging efficiency becomes 71%, which is better than our target with Hyper-Kamiokande. To realize the target efficiency, dark rate of photodetector should be reduced and vertex fitter should be more precise.

Figure 2. The number of hits in 10 ns (Dark rate: 3.0, 4.2, 6.0, 8.4 kHz). The blue line shows all 2.2 MeV $\gamma$ events, and meshed red and filled green region shows the distribution of tagged events with true and reconstructed vertex. Red broken line shows threshold

| Dark rate | 3.0 kHz | 4.2 kHz | 6.0 kHz | 8.4 kHz |
|-----------|---------|---------|---------|---------|
| True vertex | 71.0% | 67.3% | 60.1% | 53.5% |
| Reconstructed vertex | 68.7% | 63.8% | 56.5% | 48.5% |

Table 1. Tagging efficiency of detectors with different dark rate

4. Next step
As a next step, both the improvement of tagging efficiency and implementation of more realistic study are necessary. First of all, the tagging efficiency has position dependence. By setting different likelihood threshold in some regions in the detector, the tagging efficiency can be increased. And this neutron tagging analysis has not considered the radiation from radioactive isotope in the PMTs, water and so on. Therefore, by the neutron tagging background measurement in Super-Kamiokande, we should search for the origin of radiation quantitatively.

5. Summary
Neutron tagging algorithm has been developed to improve the physics capability of Hyper-Kamiokande for the separation of neutrino and anti-neutrino and background rejection in proton decay search. Currently the algorithm can separate the neutron capture signal and the accidental background from dark noise, and the neutron tagging efficiency in the neutron capture event candidates from accidental background and signal are evaluated. When the dark rate is the same as current baseline design, the tagging efficiency with true (reconstructed) vertex becomes 53.5% (48.5%). As a next step, other background sources, such as radioactive isotope inside the detector, should be evaluated using the Super-Kamiokande data.

References
[1] The Hyper-Kamiokande Experiment, Francesca Di Lodovico, (available on http://neutrino2016.iopconf.
org/IOP/media/uploaded/EVIOP/event_948/Hyper-Kamiokande_noamination.pdf)