Low-energy triggering for Hyper-Kamiokande

T Dealtry\textsuperscript{1}, G Barr\textsuperscript{2}, D Dewhurst\textsuperscript{2}, T Nicholls\textsuperscript{3}, F Nova\textsuperscript{3},
H M O’Keeffe\textsuperscript{1}, B Richards\textsuperscript{4}, S Short\textsuperscript{4} and T Stewart\textsuperscript{3} for the Hyper-Kamiokande proto-collaboration

\textsuperscript{1}Lancaster University, Physics Department, Lancaster LA1 4YB, UK
\textsuperscript{2}Oxford University, Department of Physics, Oxford OX1 3PU, UK
\textsuperscript{3}STFC, Rutherford Appleton Laboratory, Harwell Oxford OX11 0QX, UK
\textsuperscript{4}Queen Mary University of London, School of Physics and Astronomy, London E1 4NS, UK

E-mail: t.dealtry@lancaster.ac.uk

Abstract. Hyper-Kamiokande is a proposed neutrino physics and proton decay experiment in Japan, due to start operations in 2026. In order to successfully achieve the low-energy ($\lesssim$10 MeV) physics aims, a dedicated high-efficiency low-energy trigger is required. The test vertices trigger can, for a fixed noise trigger rate, reduce the electron energy trigger threshold by $\sim$2 MeV, compared with the simple NHITS trigger.

Hyper-Kamiokande (HK) \cite{1} is a next generation underground water Cherenkov detector, based on the highly successful Super-Kamiokande experiment (SK) \cite{2}, due to begin operations in 2026. The reference design consists of two 74 m (diameter) $\times$ 60 m (height) cylindrical water tanks, with a combined total (fiducial) mass of 0.52 (0.37) Mton. The detectors will be located $\sim$650 m ($\sim$1,750 m water equivalent) underground, at Tochibora mine, Gifu prefecture, Japan. A staged approach will be followed, in which the second tank begins data taking six years after the first. Each tank has two optically-separated regions: the inner detector has a 40\% photocoverage provided by $\sim$40,000 50 cm diameter photomultiplier tubes (PMTs); the outer detector uses $\sim$6,700 20 cm diameter PMTs for an active veto. New PMTs will be used for the ID, with a doubled Cherenkov photon detection efficiency, and a superior timing resolution and photon counting performance, relative to SK. The PMTs are still in development, but it is estimated that the dark noise rate will be 8–9 kHz per ID PMT, approximately twice that of SK. Assuming data hits of 12 bytes, the ID raw data rate will be $\sim$5 GB/s, dominated by dark noise. An efficient trigger will allow this large dark rate to be suppressed, allowing a cheaper and more easily scaleable data acquisition system to be used, and has the added benefit of requiring less CPU time to analyse the data offline.

HK will study a wide range of physics topics, with a variety of sources, including: CP violation in the lepton sector ($\delta_{\text{CP}}$) and precision measurement of neutrino oscillations (mass hierarchy, $\theta_{23}$ octant) using beam and atmospheric neutrinos, nucleon decay, and observations of astrophysical neutrinos. Table 1 shows the typical energy of events from different sources that HK will study, and timing parameters that affect the required complexity of the trigger. Beam neutrinos will be triggered on with the known timing information, while atmospheric neutrinos and proton decay can be triggered on efficiently using the NHITS algorithm (see below) with a high threshold (i.e. well above the dark noise background). Solar neutrinos are more challenging; at low electron energies, the number of hits per MeV is $\sim$14, therefore for solar neutrinos the signal-to-noise
Table 1: Parameters that affect triggering simplicity for different types of physics sources.

| Physics source            | Total energy | Known time? | Clustered in time? |
|---------------------------|--------------|-------------|--------------------|
| Beam neutrinos            | ∼1 GeV       | ✓           | x                  |
| Atmospheric neutrinos     | ∼1–10 GeV    | x           | x                  |
| Proton decay              | ∼1 GeV       | x           | x                  |
| Supernova burst neutrinos | ∼10 MeV      | x           | ✓                  |
| Solar neutrinos           | ∼1–10 MeV    | x           | x                  |

Table 2: Main parameters of interest for low-energy triggering using the ID for SK and HK.

|                        | SK     | HK    |
|------------------------|--------|-------|
| Number of ID PMTs      | 11146  | 44028 |
| Maximum light travel time in ID (ns) | 200    | 400   |
| Dark rate per ID PMT (kHz) | 4.2    | 8.4   |
| Noise hits in trigger decision window | ∼9     | ∼148  |

ratio is ≤1 (see table 2). Supernova burst neutrinos are somewhat easier to identify, using a cluster of low-energy triggers.

SK employs the *NHITS* trigger algorithm, which proceeds as:

1. Sum hits in a sliding time window, with width defined by the maximum light travel distance in the ID (∼400 ns for HK);
2. If above an NHITS threshold, issue a trigger.

In the case of a “super low-energy” (SLE) trigger (i.e. the lowest NHITS threshold), a level two trigger is employed in which events low-energy reconstruction is performed; events reconstructed to be near the detector wall are rejected as likely PMT glass radioactivity [3].

For HK, it is expected that performing full low-energy reconstruction will be prohibitive, due to the increase in the raw number of hits (≥ ×5), and the reduction of the signal-to-noise ratio. Therefore an alternative level two trigger is required to trigger the low-energy events while rejecting backgrounds. For this purpose the *test vertices* algorithm has been developed, which uses an approximate reconstruction. A cylindrical grid of test vertices is formed, with a default spacing of $L = 5\text{ m}$\(^1\). Then for each vertex hypothesis, the algorithm proceeds as:

1. Correct the PMT hit time distribution using the time-of-flight to the vertex;
2. Sum hits in a sliding time window, with width defined by the grid spacing (∼18 ns);
3. If above an NHITS threshold, issue a trigger\(^2\).

An example event showing how effective the time-of-flight correction is for reducing the effect of the dark-noise background is shown in figure 1.

\(^1\) The actual vertical, radial, and angular spacings are defined such that there are an integer number of test vertices with equal spacing in each direction.

\(^2\) If multiple test vertices cause a trigger at the same time (within 500 ns), the vertex with the highest sum is chosen. If there are multiple with the same sum, the vertex with the latest time, and then the vertex closest to the detector centre is chosen.
Figure 1: Hit time distribution of an example 5 MeV electron particle gun event, separating signal (filled red) and background (hashed black). (a) Raw hit times. (b) Time-of-flight corrected hit times, for the best test-vertex hypothesis.

Figure 2: Noise trigger rate for fixed 50% (90%) trigger efficiency comparing the NHITS □ (○) and test vertices ■ (●) triggers, as a function of true electron energy.

Figure 3: Trigger rate for 5 MeV electron signal + dark noise (■) and radioactivity + dark noise (●), as a function of reconstructed position for the test vertices trigger.

Figure 2 shows a comparison of the noise trigger rate for the two algorithms. The NHITS threshold is independently calculated at each point using electron particle gun Monte Carlo in the HK detector simulation WCSim [4], including the effect of dark noise and radioactivity of the PMT glass and water, and fixing the trigger efficiency for these events to 50% or 90%. Using the test vertices algorithm, the electron energy threshold can be reduced by ~2 MeV for a given trigger rate. Further improvements can be achieved by cutting on the best-reconstructed vertex; figure 3 shows that 70% of radioactive backgrounds can be suppressed for a 24% loss of water volume.

References
[1] Abe K et al. (Hyper-Kamiokande proto-collaboration) 2016 Hyper-Kamiokande Design Report KEK Preprint 2016-21, ICRR-REPORT-701-2016-1
[2] Fukuda S et al. (Super-Kamiokande collaboration) 2003 Nucl. Instrum. Meth. A 501 418–62
[3] Hosaka J et al. (Super-Kamiokande collaboration) 2006 Phys. Rev. D 73 112001 (Preprint hep-ex/0508053)
[4] WCSim URL https://github.com/WCSim/WCSim/