Large area photo-detection system using 3” PMTs for the Hyper-Kamiokande Outer-Detector

Stephane Zsoldos
King’s College London, Department of Physics, Strand, London WC2R 2LS, United Kingdom
E-mail: stephane.zsoldos@kcl.ac.uk

Abstract. Hyper-Kamiokande, scheduled to begin construction as soon as 2020, is a next generation underground water Cherenkov detector, based on the highly successful Super-Kamiokande experiment. It will serve as a far detector, 295 km away, of a long baseline neutrino experiment for the upgraded J-PARC beam in Japan. It will also be a detector capable of observing — far beyond the sensitivity of the Super-Kamiokande detector — proton decay, atmospheric neutrinos, and neutrinos from astronomical sources.

An Outer Detector (OD) consisting of PMTs mounted behind the inner detector PMTs and facing outwards to view the outer shell of the cylindrical tank, would provide topological information to identify interactions originating from particles outside the inner detector. Any optimization would lead to a significant improvement for the physics goals of the experiment, which are the measurement of the CP lepton phase and the determination of the neutrino mass hierarchy.

An original setup using small 3” PMTs is being designed for the Hyper-Kamiokande OD. They would give better redundancy, spatial, and angular resolution, as they would be twice or three times more photosensors that the original 8” design proposal of the experiment, and for a reduce cost. Several 3” PMTs candidates considered for the Hyper-Kamiokande OD have been characterized at Queen Mary University London. They all show a very low dark counts and good collection efficiency, which makes them excellent choice to be used in the experiment.

1. Introduction

Hyper-Kamiokande[1] (Hyper-K) is the successor of the Super-Kamiokande[2] (Super-K) experiment which was awarded with the Nobel Prize in 2015 for the joint discovery with the SNO[3] experiment of atmospheric neutrino oscillations. Compared to Super-K, this new experiment will consists of two cylindrical water tanks that are 72 m in height and 68 m in diameter, for a total volume up to 0.5 Mm$^3$ per tank.

Hyper-K will be a multipurpose neutrino detector with a rich physics program that aims to address some of the most significant questions facing particle physicists today. Oscillation studies from accelerator, atmospheric and solar neutrinos will refine the neutrino mixing angles and mass squared difference parameters and will aim to make the first observation of asymmetries in neutrino and antineutrino oscillations arising from a CP-violating phase, shedding light on one of the most promising explanations for the matter-antimatter asymmetry in the Universe. The search for nucleon decays will probe one of the key tenets of Grand Unified Theories. In the case of a nearby supernova, Hyper-K will observe an unprecedented number of neutrino events, providing much needed experimental results to researchers seeking to understand the mechanism of the explosion. Finally, the detection of astrophysical neutrinos from sources such as dark
matter annihilation, gamma ray burst jets, and pulsar winds could further our understanding of some of the most spectacular, and least understood, phenomena in the Universe.

Hyper-K detectors consist of a cylindrical tank filled with a quarter million tons of water. Facing inwards arranged against the inner wall of the cylinder will be hundreds of thousands of Photo Multiplier Tubes (PMTs) capable of detecting the faint signatures of neutrinos interacting with water (the Inner Detector, ID).

An Outer Detector (OD) consisting of PMTs mounted behind the ID PMTs and facing outwards to view the outer shell of the cylindrical tank, would provide topological information to identify interactions originating from particles outside the ID. The OD is an essential element of Hyper-K that will serve as a highly granular instrument for identifying and removing background events.

2. Mass Hierarchy sensitivity

The determination of the neutrino mass hierarchy is one of Hyper-K’s main goals, in concert with the leptonic CP phase $\delta_{CP}$ measurement, which can be done using accelerator or atmospheric neutrinos. For the latter, they provide excellent sensitivity to many of the remaining open questions in oscillation physics.

As atmospheric neutrinos span both low and high energies as well as long and short path lengths, they are in principal sensitive to all parameters to test the PMNS matrix unitarity. That being said, the most apparent oscillation features are driven by the so-called atmospheric mixing parameters, $\theta_{23}$ and $\Delta m_{32}^2$, and they induce a deficit of observed upward-going $\nu_\mu$ interactions at predominantly multi-GeV energies as these neutrinos oscillate into primarily unobserved $\nu_\tau$. Matter-induced parametric oscillations [4] [5] in the energy range between 2 to 10 GeV lead to significant enhancement of the appearance probability for upward-going neutrinos depending upon the mass hierarchy. For the normal (inverted) hierarchy neutrino (antineutrino) oscillations are enhanced. This enhancement leads to appearance probabilities around 50% for both hierarchies. The separation of atmospheric neutrino data into neutrino-like and antineutrino-like subsets can therefore be used to extract the hierarchy signal.

There are three basic event topologies used in the atmospheric neutrino analysis which cover different neutrino energies. The fully-contained (FC) sample includes events with vertices inside the fiducial volume which stop before leaving the ID. It is the lowest-energy sample ranging from a few hundred MeV up to about ten GeV. The partially-contained (PC) sample contains events that have vertices in the fiducial volume, but produce leptons that leave the ID. They have long tracks and so are almost exclusively from $\nu_\mu$ interactions and range in energy from a few GeV up to tens of GeV. These events have better direction resolution than FC events due to their higher energy, but worse energy resolution since the exiting muon carries some energy out of the detector. Upward-going muon events contain muons that start in the surrounding rock and then enter and pass through the OD into the ID. This sub-sample also starts at a few GeV but extends up to hundreds of TeV. These events are only included if they are up-going, where the bulk of the Earth has shielded the detector from the otherwise overwhelming cosmic-ray muon.

Increasing the Mass Hierarchy sensitivity for Hyper-K is possible by working on two research axes: First of all, since the analysis is based on the electron appearance in atmospheric neutrino samples, any substantial improvement expanding the fiducial volume of the detector would lead to an increase in statistics and therefore a better sensitivity. This can be tackled both using software and hardware development. Recently, Super-K has published results using a new reconstruction software called fiTQun [6] now able to reconstruct up to 6 Cherenkov rings produced by electron, muon, or pion particle hypotheses. This allowed them to increase the volume accessible to the analysis by 32% [7]. Hyper-K will obviously use this reconstruction algorithm, and more developments are also expected thanks to research in the area of Machine Learning for example.
Secondly, we identified that the biggest systematic error contribution comes from the energy scale calibration, which is about 1 to 2% depending on Super-K runs. The analysis select events with reconstructed energy between 2 and 10 GeV. Calibration at this level is performed using sidebands from GeV stopping muons. Therefore any improvements on the sensitivity to PC events, and better calorimetry by reconstructing exiting events, could also lead to a sensible improvements to the Mass Hierarchy sensitivity.

To address both of these issues, we proposed a novel design for the Hyper-K OD, using a large area of small 3” PMTs. An increased number of PMTs even at the expenses of a smaller area covered by the photo-cathodes allow for a better signal redundancy, with also better spatial and angular resolution.

3. Hyper-K Outer Detector: performances from selected design

We have implemented into the dedicated simulation package of Hyper-K, WCSim [8], a fully working OD sub-element, with separated PMT collection including its electronics. We considered for this study 3 different geometries inside the OD: 13.3k or 18k 3” PMTs, which are compared to the main design from the Super-K OD, 6.7k 8” PMTs. These designs corresponds to 0.28%, 0.42% and 1% photo-coverage area, respectively. To increase the light collection inside the OD, each PMTs are coupled with a wavelength-shifting (WLS) plate. They re-emit light absorbed in the UV spectrum at 420 nm, where the PMT collection efficiency is peaked. These plastic plate have refraction indices about $n = 1.56$ which allows total reflection for re-emitted photons below 1 rad (or 57°). By choosing the plate area to be 60x60 cm², we estimated that we can achieve a factor 3 increase in the light collection for 3” PMTs, matching the photo-coverage of 1% for the 13.3k design, which is the baseline design for the OD. Fig. 1 shows the light shifting in action for a Super-K OD PMT coupled to a Kuraray WLS plate.

![Super-K OD Hamamatsu R5912 PMT coupled with a Kuraray WLS plate under an UV lamp.](image)

Several 3” PMTs from Hamamatsu, ETEL and HZC are considered for the OD and a selection criteria has been developed to chose the most appropriate model. As the OD hits integrated charge will be the main information used for veto and classification purposes, a huge effort has been drawn to measure precisely the dark rates as an increased number of PMTs could lead to an increased number of dark coincidences. A previous study [9] has been dedicated to characterize the PMTs dark rates, and Fig. 2 shows that the number of dark counts doesn’t scale linearly with the photo-coverage area for 3” and 8” PMTs, as the 3” tubes exhibits 10 times less dark rates.
Figure 2. Number of dark counts expected in the OD w.r.t to the photo-coverage area, for 3" (in red) and for 8" (in blue) PMTs, assuming the measured value of 400 Hz and 4 kHz in average respectively.

Our preliminary results focused on the veto power rejection and reconstruction capabilities using only OD hits for cosmic muons. We have developed a custom generator using the expected cosmic flux at Hyper-K, extrapolated from the Super-K measurement using the surroundings profile at Hyper-K site. We measured that we can achieve a 100% veto efficiency using $N_{\text{Hits}} = 50$ OD Hits with any geometries considered. This value is a typical number extracted from Super-K OD rejection cuts. Furthermore, we also study the number of hits in the OD with respect to the energy of the incoming cosmic muons, using linear and exponential fits. Our results shows that using 18k of 3" small PMTs, we can improve the fit $\chi^2$ and increase the resolution — defined by the slope of the linear fit — compare to the baseline design with 6.7k 8" PMTs. Fig. 3 shows in a table a summary of the fit results for each geometries considered.

In summary, we have identified a niche area where we can improve, using better hardware and software solutions, the mass hierarchy sensitivity of Hyper-K by using an alternative design of the OD. This setup using a large area of small 3" PMTs offers a reduced cost from the baseline design derived from Super-K and better reconstruction of cosmic muons energy.

References
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