PROCEEDINGS OF SCIENCE

Precision measurements of photosensor components for the Hyper-Kamiokande Outer Detector

Soniya Samani[a,*] **for the Hyper-Kamiokande Collaboration**

[a] *Department of Physics, University of Oxford, Keble Road, Oxford, OX1 3RH, United Kingdom*

E-mail: soniya.samani@physics.ox.ac.uk

The Hyper-Kamiokande (HK) experiment will be a next-generation water Cherenkov detector capable of measuring neutrino interactions with unprecedented statistical precision. Discriminating neutrino events from cosmic-ray muons and low-energy backgrounds is dependent upon constructing an effective Outer Detector (OD). The baseline design proposes deploying up to 10,000 3-inch high-sensitivity photomultiplier tubes each coupled to acrylic Wavelength Shifting (WLS) plates. Sophisticated optical measurements using a high-powered laser setup have improved on existing absorbance results and demonstrated a previously unknown artefact of Mie Scattering present in all candidate WLS samples. This combined with future measurements from a new test facility (Baby-K), designed to evaluate the light collection efficiency of all WLS plates via their response to cosmic muons in distilled water, will enable robust evaluation of all candidate WLS plate properties. An overview of the ongoing R&D effort to optimise the OD photosensor design, including the latest water and air-based measurements of WLS samples is discussed in this contribution.

41st International Conference on High Energy physics - ICHEP2022
6-13 July, 2022
Bologna, Italy

*Speaker

PoS(ICHEP2022)363

1. The Hyper-Kamiokande Detector

Hyper-Kamiokande (HK) will be the next generation water Cherenkov experiment that will leverage the high-intensity neutrino beam from JPARC to host a vastly diverse physics program. Physics targets include constraining oscillation parameters to unprecedented precision, probing the neutrino mass-ordering and measuring Charge-Parity (CP) violating phases in the leptonic sector [1].

HK foresees the construction of an ultra-pure water tank, 71 m in height and 68 m in diameter, with a 188 kton fiducial mass to provide an effective volume 8.4 times larger than its predecessor Super-Kamiokande (SK) [2]. The detector will be deployed at the Tochibora site in Japan with a rock overburden of 650 m. PMT support structures will optically separate the tank into regions containing the Inner Detector (ID) and the Outer Detector (OD) to follow the well-established design of SK. The ID will contain an inward-facing array of 20,000 Box&Line 20-inch PMT's that delivers competitive timing and charge resolution whilst doubling the photon-detection efficiency of SK PMTs [3]. An additional $\sim$ 5000 multi-PMTs each housing nineteen 3-inch PMTs will be instrumented in the ID for improved segmentation [4].

The OD primarily operates as a photon counter by identifying clusters of hits above a threshold defined by the dark rate of the PMTs to serve as an active veto against backgrounds. Therefore, design optimisation is an essential task within HK's extensive R&D program. The barrel and endcaps will have a 1 m and 2 m water thickness respectively within which up to 10,000 PMTs will be instrumented. MC studies demonstrated that using 90% reflective Tyvek maximises light collection and compensates for the relatively sparse PMT arrangement. Mounting 30×30 cm Wavelength Shifting (WLS) plates around the bulb of each PMT further enhances the light yield and recovers the Ultra-Violet (UV) portion of the Cherenkov spectrum [5]. Optimal selection of the WLS plastic requires precision optical measurements of all samples over the UV-VIS range.

2. Optical Properties of Wavelength Shifting Plates

UV-VIS spectrophotometry is used in this work to quantify the optical properties of WLS plastics in air. Since commercially sourced WLS samples from Kuraray, Eljen and LabLogic use various organic fluorescent compounds (fluors) with unspecified chemical compositions and concentrations, measuring the relative absorbance spectra (A) is crucial for evaluating performance [6]. This technique involves comparing the intensity (I) of laser light transmitted (T) through a sample with respect to the incident intensity (I_0), as shown in the schematic diagram in Figure 1 (left).

$$T = \frac{I}{I_0} \qquad\qquad A = -ln(T) \tag{1}$$

In WLS plastic, light is absorbed via two prominent mechanisms; active and passive absorption. The former exclusively refers to the behaviour of the fluor, which is homogeneously distributed within a polymer base. This absorbs UV light and isotropically re-emits into the visible blue to match the spectral sensitivity of the PMT, whereas passive absorption occurs due to absorption and dissipation of light in the polymer base. Fresnel reflection at normal incidence accounts for approximately $8\% - 10\%$ light loss at the air-plate boundary, which is integrated into all measurements [5]. The

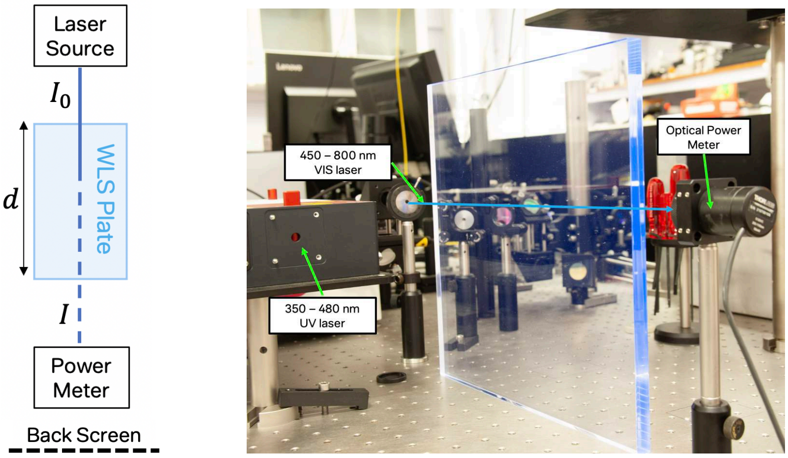

Figure 1: Schematic diagram of an optical measurement setup (left). Photograph of the experimental setup with a Kuraray WLS sample (right).

transmittance and the length of the sample (d) is used to calculate the attenuation length ($\mu_{eff}(\lambda)$),

$$\mu_{eff}(\lambda) = -\frac{d}{ln(T(\lambda))}. \tag{2}$$

The reduction in the intensity of transmitted light observed due to the combined action of absorption and reflection is described by Beer-Lambert's Law, where Equation 3 shows the probability of absorption [7],

$$P(\lambda) = e^{-\frac{d}{\mu_{eff}(\lambda)}}. \tag{3}$$

All quantities are effective since the relation between absorbance and pathlength are only strictly valid for a homogeneous medium with no re-emission of light.

3. Optical Setup

To measure such parameters, we use a setup that consists of a SuperK Extreme supercontinuum laser with two filters that provides a single-line laser with a tuneable coverage between 350 – 800 nm. WLS plates are orientated such that the beam propagates through the longest optical pathlength possible (20 < d < 30 cm), as depicted in Figure 1 (right). A calibrated silicon photodiode with a 9.5 mm diameter aperture connected to a Thorlabs PM400 power meter is carefully aligned at the exit point of the sample. Absolute power measurements are made in 2 nm and 5 nm increments for the UV and VIS laser filters respectively for all WLS plates.

4. Absorbance and Attenuation Length Spectra

Visual inspection of light projected onto a back screen highlights the prominent effect of Mie Scattering, a previously unknown artefact of these WLS plastics. Impurities, polymer molecule clusters and undissolved fluors create small local non-uniformities in density which become centres for deflecting light [8]. Scattering from such microstructures with dimensions comparable to the wavelength of light, known as the Mie Effect, occurs predominately in the forward direction [9].

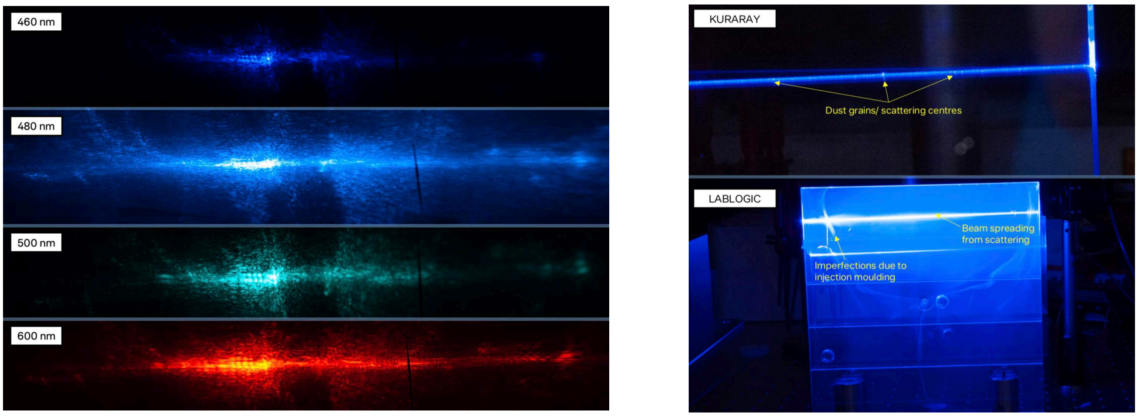

Figure 2: Interference observed from Mie scattering in the LabLogic WLS sample (left). Impurities, dust grains and surface inclusions in labelled samples (right).

Figure 2 shows interference fringes produced when light scatters by this mechanism in the WLS plastic. Upward and downward scatters are absorbed due to the orientation of the plates such that a pattern elongated in the horizontal remains. Scattering becomes less pronounced with increasing incident wavelength since Mie scattering is wavelength dependent [8]. Surface inclusions from the fabrication process (injection moulding) of the LabLogic sample further amplifies scattering to the point where the beam entirely diffuses into the plastic. Since scattering is automatically integrated into the observed transmission loss it is extremely difficult to distinguish intrinsic light absorption from scattering.

Figure 3 shows the measured absorbance and attenuation length spectra for several candidate WLS plates [1]. All samples exhibit high absorptivity with less than 10% light transmission below 400 nm due to the net effect of active and passive absorption. An absorbance measurement that exceeds 1 is subject to large uncertainty due to the lack of precision in measuring low light intensities. Small deviations in the transmittance typically induces large changes in the measured absorbance due to the logarithmic relationship described in Equation 2. However, using a highly-sensitive power sensor with 1 nW resolution facilitates precision measurements even at low transmittance, such that performance in the UV region is well defined for all samples.

Most samples are mostly optically transparent above 400 nm since active absorption falls off and light is predominately attenuated by scattering. The scattering effect modifies the absorbance and attenuation length spectra significantly depending on sample thickness, density and uniformity of scattering centres. Consequently, all measurements register higher absorptivity due to the fraction of scattered light that fails to reach the detector. Mie scattering is clearly dominant in the LabLogic spectra since the plastic is virtually opaque at all wavelengths whereas all other samples exhibit optical clarity in the region where re-emission peaks. These results establish a useful parameter for evaluating the relative performance of WLS samples in line with the requirements of the HK-OD and highlight the importance of carrying out water-based WLS measurements.

[1]Spectra for Sheffield, SK-OD, Eljen and Kuraray original samples that were measured with a spectrophotometer setup and are shown for reference [6].

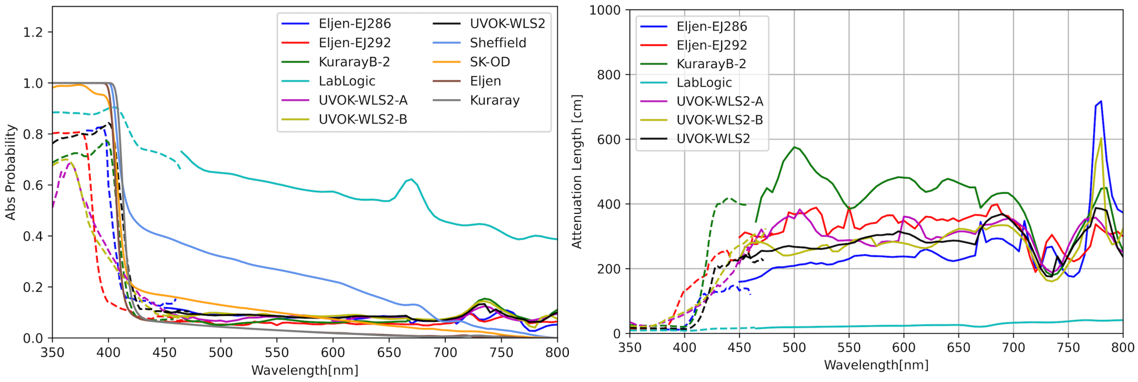

Figure 3: Absorbance (left) and attenuation length spectrum (right) measured as a function of wavelength for several candidate WLS samples. Measurements taken with UV laser filter (dashed) and with VIS laser filter (solid) are shown.

5. The Baby-K Water-Based WLS Test Facility

The Baby-K water-based test facility is designed to evaluate the light collection efficiency of candidate WLS plates via their response to cosmic muons in distilled water. Characterisation of WLS samples under such experimental conditions provides a relative performance based on the combination of all optical and material properties. Measurements aim to guide the selection of WLS plate to optimise performance of the HK-OD photosensor unit.

The setup consists of a Hamamatsu R6091 flat-faced PMT (ffPMT) operating at 1700 V mounted inside a cylindrical 58.4 × 87.6 cm steel drum. WLS plates are suspended by four brackets with adjustable clamps that hermetically seal the photosensor components together via press-fitting. This ffPMT-WLS plate configuration mitigates inconsistencies in the press-fit quality that are present when using a hemispherical PMT, such as variations of the PMT's bulb diameter, contour, surface finishes and tolerances of the machined hole/injection mould. A thin layer of BC-630 silicon grease spread between the PMT-WLS interface creates a region with an intermediate refractive index that maximises the optical contact and light transmission. The detector volume is filled with ~ 200 L of distilled water to serve as an optically clear Cherenkov medium for cosmic muons. PMT gain

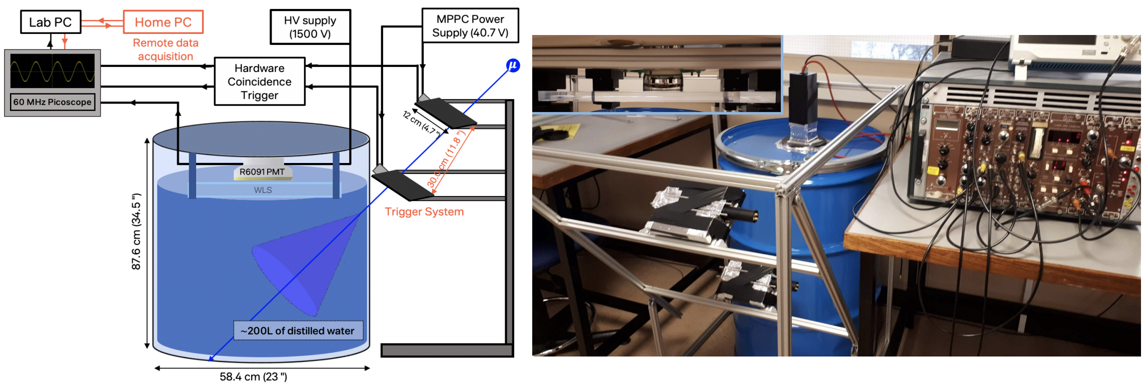

Figure 4: Schematic diagram (left) and photograph (right) of the Baby-K test setup.

variation and the water absorbance spectra will be measured regularly to monitor water degradation over the experiment's lifetime. The trigger system is formed of two plastic scintillator paddles with a 12×12 cm effective area that restricts the solid angle of cosmic muons incident on the tank. Hamamatsu S14160-6050HS $6{\times}6$ mm Silicon Photo-Multipliers (SiPMs) are surface mounted onto each paddle edge. The scintillator paddles are fixed in parallel to an adjustable stand that provides variable angular acceptance of incident cosmic muons. NIM electronics in hardware are used to amplify and combine the SiPM pulses into a logic coincidence pulse that is then fed into a Picoscope 5000 series for data acquisition. Following the completion of the detector setup and calibration of the hardware coincidence trigger, measurements of WLS samples are currently underway.

6. Conclusion

Extensive testing of photosensor components and evaluation of candidate WLS samples for optimisation of the HK-OD photosensor is ongoing in both air and water-based experimental setups. UV-VIS spectrophotometry using a sophisticated setup has provided precision measurements of optical properties whilst highlighting the significance of Mie scattering present in WLS plastic. This coupled with future water-based measurements of the light collection efficiency from Baby-K will enable robust characterisation of WLS sample performance. Therefore, this work will be pivotal in the final selection of photosensor components for the HK-OD.

References

[1] Francesca Di Lodovico. The hyper-kamiokande experiment. *Journal of Physics: Conference Series*, 888:012020, sep 2017. IOP Publishing.

[2] K. Abe et al. Hyper-Kamiokande Design Report. 5 2018. arXiv.

[3] Yoshitaka Itow. Construction status and prospects of the Hyper-Kamiokande project. *PoS*, ICRC2021:1192, 2021.

[4] J.R. Wilson. The hyper-kamiokande experiment. *Journal of Physics: Conference Series*, 2156(1):012153, dec 2021. IOP Publishing.

[5] P. Soler and Z. H. Wang. Optical properties of wavelength shifting panels. *Nucl. Instrum. Meth. A*, 324:482–490, 1993.

[6] Mahdi Taani. *Non-Standard Neutrino Interaction Analysis with Atmospheric Neutrino Data in Super-Kamiokande I-IV and the Design of the Hyper-Kamiokande Outer Detector*. PhD thesis, Nagoya University/The University of Edinburgh, Edinburgh U., 2020. Edinburgh Archive.

[7] Thomas G. Mayerhöfer, Susanne Pahlow, and Jürgen Popp. The bouguer-beer-lambert law: Shining light on the obscure. *ChemPhysChem*, 21(18):2029–2046, 2020.

[8] Christian-Alexander Bunge, Roman Kruglov, and Hans Poisel. Rayleigh and mie scattering in polymer optical fibers. *Lightwave Technol.*, 24(8):3137, Aug 2006.

[9] A. L. Fymat and K. D. Mease. Mie forward scattering: improved semiempirical approximation with application to particle size distribution inversion. *Appl. Opt.*, 20(2):194–198, Jan 1981.