PROCEEDINGS OF SCIENCE

Development of the Wavelength-Shifting Plate Light Collector for the Outer Detector of Hyper-Kamiokande

Alexander Izmaylov,[a,*] **Gleb Erofeev,**[a] **Alexei Khotjantsev,**[a] **Yury Kudenko,**[a] **Oleg Mineev**[a] **and Nikolai Yershov**[a]

[a] *Institute for Nuclear Research, INR RAS,*
60-letiya Oktyabrya prospekt 7a, 117312 Moscow, Russia

E-mail: izmaylov@inr.ru

The paper describes the developments of the Wave-Length Shifting (WLS) plates for the photon collection units of the Outer Detector (OD) of the Hyper-Kamiokande next generation water Cherenkov detector currently under construction in Japan. The unit consists of a 3-inch PMT mounted inside a WLS plate so to further maximise the amount of the collected light. Such plates collect Cherenkov light, re-emit it in a longer wavelength spectrum and concentrate on the PMT thus increasing the effective acceptance for the Cherenkov radiation. The broad R&D program includes optimisation of the chemical composition of the plates, their shape and geometry, coupling between PMTs and the WLS plates, selection of the chemical reflector to cover the sides. Various measurements of the prototypes of the PMT+WLS plate units were carried out with the UV LED sources in air and water, studies of the dark rate and aging were also performed. The corresponding results are presented in the paper.

6th International Conference on Technology and Instrumentation in Particle Physics (TIPP2023)
4 - 8 Sep 2023
Cape Town, Western Cape, South Africa

*Speaker

PoS(TIPP2023)112

1. Introduction

The Hyper-Kamiokande (Hyper-K, Japan) [1] is a next-generation water Cherenkov detector expected to lead the neutrino studies in the coming decade. The physics of the Hyper-K is rich and includes measurements with accelerator, solar, atmospheric and cosmic neutrinos, as well as the search for proton decay. The detector is a cylindrical tank 68 m in diameter and 71 m in height (Fig. 1), with a total mass of 258 kilotons of water. The effective volume will be approximately an order of magnitude larger than its predecessor, the Super-Kamiokande (Super-K) detector [2].

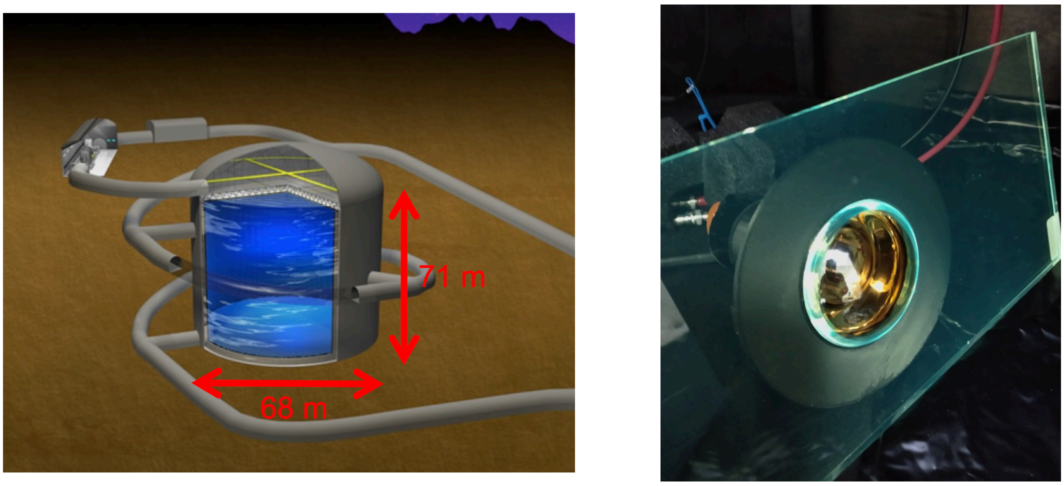

Figure 1: Left: schematic of the Hyper-Kamiokande detector. Right: photo of a prototype of the Hyper-K OD module, a PMT inside a WLS plate.

The Hyper-Kamiokande tank is optically divided into two regions: the inner ("Inner Detector", ID) and outer ("Outer Detector", OD) detectors. In the inner detector with the mass of 217 kilotons, 20,000 photomultiplier tubes (PMT) will be used to register the light signal. The PMTs will be Hamamatsu R12860 (Japan) devices with a diameter of 50 cm and Box&Line type dynode. These PMTs provide a higher (~+50% compared to R3600 in Super-K) quantum efficiency, approximately twice as good charge and time resolution, which will compensate for a lower overall percentage of the photocathode coverage: 20% versus 40% in Super-K. In addition, around 1,000 modular PMTs will be used, each consisting of 19 8 cm individual counters inside a common housing.

The outer detector area will be recorded by PMTs located behind the ID counters and directed outward. The OD water layer is 2 m at the top and bottom of the detector and 1 m on the sides. The main purpose of the OD is to record backgrounds originating outside the inner detector, such as cosmic muon tracks, as well as to detect the activity from the ID to identify fully contained objects. The Hyper-K detector will be located in an underground cavern, shielded by approximately 1750 m of water equivalent. The smaller overburden and larger dimensions result in an increased cosmic muon flux compared to Super-K: ~ 2 Hz $\rightarrow$ $\sim$45 Hz (4×10^6 muons/day). The outer detector will use around 3600 8 cm (3-inch) PMTs, a key task is to increase the efficiency of the light collection.

2. Light-collection System in the Hyper-K OD

The light-detection module of the OD will use a PMT placed in the center of a wavelength-shifting (WLS) plate (Fig.1). Such a structure was proposed and successfully used in the IMB-2/3 [3] detector as well as in Super-K. The plates absorb Cherenkov light from charged particles in the UV range and re-emit it in the visible region (400-600 nm), in which PMTs have high sensitivity. Most of the photons are absorbed in the first 1-2 mm of the plate and are then isotropically re-emitted. Re-emitted photons are retained by the plate and can be further detected by a PMT. In addition, "leaked" photons can be reflected by the detector walls and still detected. The walls of the OD will be covered with Tyvek sheets. The requirements for the OD and its modules are as follows: cosmic backgrounds rejection at the level of 10^4, dark rate < 1 kHz (with 0.25 photoelectron, p.e. threshold), thermal power < 1 W per channel, low radioactivity level of < 1 MBq, PMTs protected from water and withstanding pressure up to 10 bar, long-term stability of the elements for about 20 years of data taking. The primary option for the OD PMTs is Hamamatsu R14374 model, NNVT 2031 PMTs (China) are also studied. Both devices have an outer diameter of 80 mm.

3. Chemical Composition of the Plates

Research work on optimization of plate parameters is carried out at INR RAS (Moscow, Russia) jointly with the Polymer Research Institute (Dzerzhinsk, Russia). PMMA-based plates with WSL fluors are manufactured using radical polymerization. The two large sides of a plate do not require additional processing after manufacturing. The final-sized plates, as well as the central openings for PMTs, are cut at INR RAS using a CO_2 laser, the edges are additionally polished using a Bermaq diamond polishing machine.

Plates with various fluors and with different fluor concentrations were produced and then tested. The following fluors were studied: BBQ – absorption region of 250-460 nm, emission region of 420-640 nm (peak at 510 nm); Bis-MSB – absorption at 300-400 nm (peak at 350 nm), emission region of 380-530 nm (maximum at 400-460 nm), similar in characteristics to POPOP, usually higher solubility in organic solvents, a concentration of 50 mg/l used in Super-K and IMB; POPOP – absorption region of 250-390 nm (peak at 360 nm), emission at 380-510 nm (maximum at 390-450 nm), widely used in plastic scintillators based on polystyrene and polyvinyltoluene (PVT), the full polymerization times for bis-MSB and POPOP are almost the same based on the studies in Dzerzhinsk; PPO – absorption region of 240-310 (peak at 280 nm), emission at 320-420 nm (maximum at 340-380 nm), effectively absorbs short UV, often used as a primary fluor in liquid scintillators; a "commercial" Eljen (USA) EJ286 PVT-based plate with its absorption maximum at 355 nm and emission at 425 nm was also used in the studies.

The Hyper-K OD PMTs have their maximum efficiency in the 350-450 nm range, reaching $\sim$30% at 400 nm.

The performance of the plates was studied using subnanosecond LED sources PicoQuant Co, the diodes with 265, 315, 380 and 405 nm light were used. Light from the source was directed to a plate through a 10 mm collimator.

The light yields obtained for different wavelengths were combined to obtain the following value, the optimization criterion (FoM, "Figure of Merit"):

$$FoM = 0.45 \times RLY_{250-300} + 0.32 \times RLY_{300-350} + 0.23 \times RLY_{350-400},$$

where "Relative Light Yield" $RLY = N_{p.e.}/N_{ph} \times 10^3$, $N_{p.e.}$ is the measured signal of the PMT, N_{ph} is the number of photons from the LED calibrated by a direct illumination of the PMT, and the values 0.45, 0.32 and 0.23 correspond to the fractions of the Cherenkov spectrum for the wavelengths of interest. The range of 250-400 nm is taken as 100%. The PMT signal was measured for three positions of the LED, at a distance of 6, 12 and 18 cm from the center, and the obtained values were averaged. The values of the FoM for different prototypes are summarised in Fig. 2, the numbers after the names of the fluors indicate the concentrations in mg/l.

Fluor	FoM
BBQ50	2.91
BBQ100	3.34
Bis-MSB50	3.81
Bis-MSB100	3.83
POPOP100	4.38
POPOP200	4.64
POPOP400	3.80
POPOP100/PPO10000	5.89
POPOP800/PPO5000	4.50
EJ286	3.34

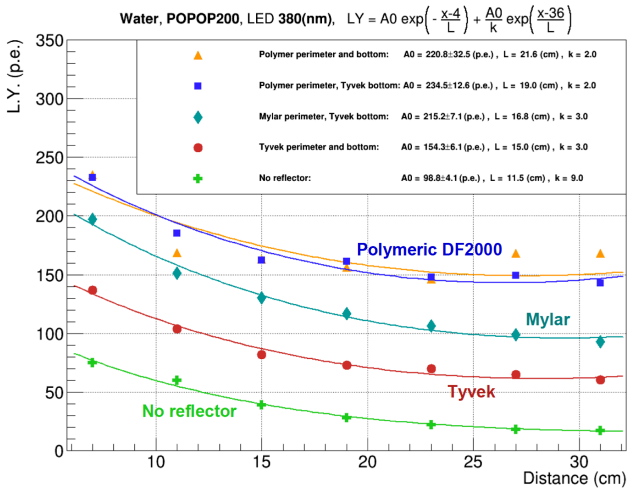

Figure 2: Left: optimization "FoM" criterion for different prototypes of the plates, plate size $40\times20\times1$ cm^3, measurements in air and without reflectors. Right: attenuation curves measured using different reflectors at the edges and the bottom side of the WLS plate, measurements in water at different distances from the center.

The efficiency of light capture in the short UV region corresponding to the maximum of the Cherenkov spectrum plays an important role. In this region the use of the PPO fluor is optimal, hence the POPOP+PPO combination, i.e. a "double-fluor" plate, was chosen as the main option. Plates with a single POPOP dopant of 100-200 mg/l also showed a relatively good result.

The light output was studied in both air and water environments. For plates without reflectors, the light output in water measured at a distance of 20-35 cm from the center decreases by about 2-3 times compared to air. This decrease is attributed to a change of the refractive index of the medium.

Different concentrations of the fluors were studied. For PPO, the optimal concentration was chosen to be 3 g/l. In the range of 3-7 g/l the performance does not noticeably change, and a higher concentration leads to a decrease in the light output. For POPOP, a concentration of 50 mg/L was chosen, which is effective in the shorter wavelength region of 250-320 nm. The combination of PPO and bis-MSB/POPOP is widely used in liquid scintillators for neutrino experiments, the concentrations of fluors are usually O(10) mg/L for bis-MSB/POPOP and 2-7 g/L for the PPO primary fluor.

To summarize, the concentrations of the fluors for an efficient registration of the Cherenkov spectrum in water by PMMA-based plates were chosen as POPOP 50 mg/L + PPO 3 g/L.

4. Geometry and size of the plates

The size of the plates was optimised based on the simulations with the WCSim toolkit [4]: 30×30 cm^2 size was set. Larger plates do not provide any significant gain in the light collection and increase the cost of the materials: the plates capture light in the UV range but for ”visible” photons they work as an additional absorber. The thickness of the plates is set to 7 mm with the optimum within 6-10 mm confirmed with both measurements and simulations, the cost of the material was also taken into account. Modeling was also used to optimize the shape of the plates: rectangular, square, triangular and round plates were considered, the shape affects the efficiency of photon concentration on the PMT. The square shaped plates were finally chosen.

Different options for the opening for placing an 80 mm PMT were studied: a cylindrical hole, an open cone and a hemispherical opening. The balance is important between the efficiencies of collection of the direct and re-emitted Cherenkov light. The most optimal shape was found to be a cylindrical hole with a diameter of 78 mm, which is consistent with the 72 mm size of the photocathode of the Hamamatsu PMTs. The chosen cylindrical shape is also easy to manufacture which is beneficial to the mass production of the plates

5. Studies of the reflector

Light collection of the plates can be further increased by using a reflector. Various options for a reflector to be put at the edges of the plate were studied: a diffuse reflector Tyvek, a mirror reflector aluminized Mylar film, a mirror reflector adhesive polymer film 3M DF2000MA. The largest effect was observed for the polymer film 3M DF2000MA (Fig. 2): an increase in light output by around two times compared to Tyvek and by ~50% compared to Mylar. A Tyvek sheet will also be placed on the back side of a plate. Although the effect for the re-emitted light is about 10%, the presence of this material serves to create a homogeneous reflective environment in the OD.

Aging tests were carried out with an exposure of four months and with the plates put in water inside a thermostat at 73 °C (~20 years of Hyper-K running). Although the temperature was too high, as the recommended upper limit for PMMA based materials is 70-80 °C, and caused PMMA degradation, the studies demonstrated good long-term stability of the 3M DF2000MA film reflector.

6. Dark-rate Measurements

The dark signal of the PMT+WLS plate module was studied in a light-insulated thermostat. Two plates, POPOP200 and POPOP800+PPO5000, were used for the tests. For 13°C (expected in the OD) the dark signal was about 400 Hz for the ”single-fluor” plate and ~800 Hz for the ”double-flour” one. The 800 Hz has contributions from the following sources:

- 200 Hz – dark rate of the PMT,

- 150 Hz – caused by photons emitted by the photocathode and then reflected back; estimated measuring the signal from the PMT with another one located in front of it, comparing the measurements with the latter turned on and off,
- 200 Hz – caused by the radioactive backgrounds in the laboratory, largely reduced with a lead block shielding; POPOP+PPO plate is more sensitive to the backgrounds,
- 250 Hz – an additional signal from the plate associated with the presence of PPO in a large concentration, does not fade away with time (~3 months); the nature is unclear, a possible cause is the thermal motion of molecules, the release of energy accumulated in optical traps.

Thus, under the conditions of the OD, the dark signal (at the threshold of 0.25 p.e.) is expected to be around 600 Hz for a plate with POPOP+PPO fluors and less than ~350 Hz in the case of a single POPOP fluor of a low concentration. The basic requirement for the dark signal level in the OD is < 1 kHz, although further optimisation may be desirable to improve the capabilities for the rejection of the backgrounds.

7. Conclusions

In order to accomplish the rich physics program of the new generation water Cherenkov detector Hyper-Kamiokande, it is crucial to have the backgrounds well controlled and suppressed. The outer detector plays an important role and the current work is focused on optimisation of its light-collection system. A 3-inch, 8 cm ⌀ PMT surrounded by a $300 \times 300 \times 7$ mm^3 sized wavelength-shifting WLS plate, is used as a photodetector element. The primary option for the PMT is Hamamatsu R14374 model. The PMMA-based WLS plates are developed at the INR RAS (Moscow, Russia) jointly with the Polymer Research Institute (Dzerzhinsk, Russia). A double-fluor cocktail with the POPOP 50 mg/l + PPO 3 g/l concentrations found to be optimal to collect light over the Cherenkov spectrum in water. An additional reflector, 3M DF2000MA polymeric film, will be placed at the edges, and a Tyvek sheet at the back side of the plate to further ehance the light collection. It is expected that the usage of the WLS plates will result in doubling the amount of the collected light.

Acknowledgements

This work was supported in part by the RSF grant 22-12-00358, Russia.

References

[1] K. Abe and H.-K. Tanaka, *Hyper-Kamiokande construction status and prospects*, *Front. in Phys.* **12** (2024) 1378254.

[2] Super-Kamiokande collaboration, *The Super-Kamiokande detector*, *Nucl. Instrum. Meth. A* **501** (2003) 418.

[3] R. Becker-Szendy et al., *IMB-3: A Large water Cherenkov detector for nucleon decay and neutrino interactions*, *Nucl. Instrum. Meth. A* **324** (1993) 363.

[4] “WCSim package.” `https://github.com/WCSim/WCSim`.