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A Wavelength-shifting Optical Module (WOM) for in-ice neutrino detectors

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Abstract. We report on the development status of a single-photon sensor that employs wavelength-shifting and light-guiding techniques to maximize the collection area while minimizing the dark noise rate. The sensor is tailored towards application in ice-Cherenkov neutrino detectors embedded in inert and cold, low-radioactivity and UV transparent ice as a detection medium, such as IceCube-Gen2 or MICA. The goal is to decrease the energy threshold as well as to increase the energy resolution and the vetoing capability of the neutrino telescope, when compared to a setup with optical sensors similar to those used in IceCube. The proposed sensor captures photons with wavelengths between 250 nm and 400 nm. These photons are re-emitted with wavelengths above 400 nm by a wavelength shifting coating applied to a 90 mm diameter polymer tube. The tube guides the light towards a small-diameter PMT via total internal reflection. By scaling the results from smaller laboratory prototypes, the total efficiency of the proposed detector for a Cherenkov spectrum is estimated to exceed that of a standard IceCube optical module. The status of the prototype development and the performance of its main components will be discussed.

1. Motivation and concept

IceCube has seen its first astrophysical neutrinos [1]. Building on this success the planned IceCube-Gen2 facility [2] will allow for collecting higher statistics of high energy astrophysical neutrinos and a determination of the neutrino mass hierarchy. Deploying new optical modules in the ice gives a unique chance to improve the optical modules in noise rate and effective area. We have developed a concept that achieves this by a wavelength-shifter (WLS) coated light guiding tube connected to small PMTs. The WLS absorbs UV light (250–400 nm) and re-emits photons isotropically in the blue (> 400 nm).

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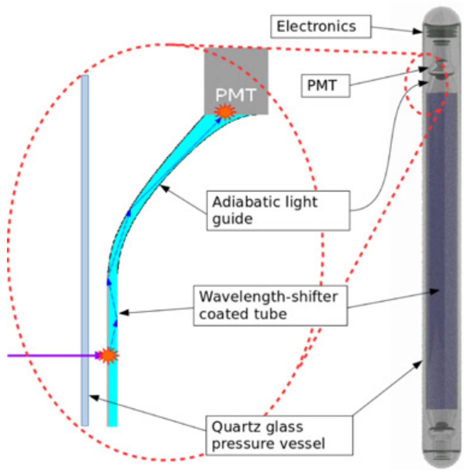

Figure 1. WOM. The working principle is sketched in a cross section. Light is absorbed by a thin layer of WLS and re-emitted isotropically at a lower wavelength. With a probability of $\approx 75\%$ the re-emitted light is captured by total internal reflection and guided towards the PMTs where it can be detected. Also shown an artists view of the full module.

Combined with the high transparency of the ice [3] the WLS allows us to access the Cherenkov photons with wavelengths $< 350\,\text{nm}$, with significant gains due to the steeply falling Cherenkov spectrum $\propto \frac{1}{\lambda^2}$. The shifted photons are detected by small and hence less noisy PMTs at the ends of the tube. This concept, the Wavelength-shifting Optical Module (WOM), provides a low cost single-photon detector, with an increased photosensitive area and reduced overall noise. In large volume detectors like IceCube-Gen2 [2] and MICA [4], this allows the energy threshold to be lowered while keeping the detector volume and amount of deployed modules constant. In addition, the large sensitive area and signal to noise ratio allows for good vetoing capabilities making this concept interesting also for experiments like SHiP [5]. The WOM as shown in Fig. 1 consists of a pressure vessel, a wavelength-shifting and light-guiding tube, an adiabatic light guide and PMTs with their readout electronics. The pressure vessel protects the sensitive components inside from the outer pressure. The pressure vessel is 1.3 m long, 114 mm in diameter and made from quartz glass in order to be transparent to UV-light. The wavelength-shifting and light-guiding tube within the pressure vessel has a diameter of 90 mm and is made of acrylic glass. The thin air layer around the tube and high refractive index difference facilitates the light guiding of the shifted light by total internal reflection (theoretical maximum 74.6%). The light captured in the tube propagates to the upper or lower end. Adiabatic light guides, glued to the ends, direct the light virtually lossless towards the PMTs. Several low noise PMTs are currently under consideration. The readout electronics will be an adapted version of the Gen2 Digital Optical Module (Gen2-DOM [6]) electronics.

2. Efficiency

We have developed a WLS paint and investigated its properties when coated on a transparent light guiding tube. The key value for the quality is the capture and transport efficiency ϵ defined as the ratio of shifted photons leaving on either side of a tube coated with a WLS paint to the amount of UV photons the tube is exposed to. This value has been measured in different ways. They all have in common that the test tube is illuminated with a small light beam perpendicular to the tube axis and the light coming out at one end is detected. The other end is blackened to reduce reflections. Since we plan for reading

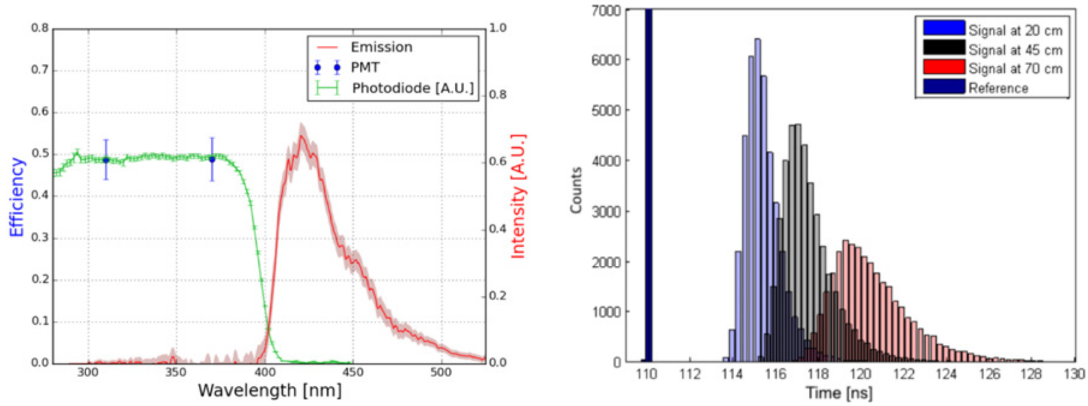

Figure 2. Efficiency ϵ of a custom made WLS paint coated on a PMMA tube for light capturing and transport measured with a photodiode and a PMT. The photodiode spectrum is scaled to match the PMT results and allows the reader to see the flatness of the spectrum. Also the emission spectrum of the same paint is shown (left). For different distances between illumination point on the tube and the PMT the broadening of the arrival time distributions is shown (right).

out both ends, we correct ϵ for this by multiplying with a factor of two. This efficiency ϵ is used as a measure to optimize the paint, for selection of the right substrate and for estimating the final detector efficiency.

2.1 WLS paint development

The paint performing best in efficiency ϵ, adhesiveness and surface quality[1], is made with a mixture of 77.31%[2] Toluene, 22.29% Paraloid B72[3], 0.13% Bis-MSB and 0.27% P-Terphenyl [7]. The efficiency and emission spectra of this paint are shown in Fig. 2 (left). To apply the paint to the substrate a dip-coating process is used, where the substrate is immersed in WLS paint and withdrawn with a well defined velocity. The higher the withdraw velocity the thicker the paint film on the substrate. With the above mixture a velocity of 9.3 cm/min has given the best absorption and surface quality.

2.2 Timing

Photon transit times through the device are affected by light paths of different lengths in the light guide and by the WLS decay time. This has been investigated with a sub-nanosecond input pulse as shown in Fig. 2 (right). For the tube of 90 cm length and homogeneous illumination an overall FWHM of ≈ 10 ns is expected.

2.3 Theoretical expectations

The efficiency ϵ had been measured with a photodiode setup in the first development stages as described in [8]. The measured values have been a factor > 2 lower than expected when considering a geometrical capture efficiency of 74.6%, 96% WLS-quantum efficiency [9] and Fresnel losses. Measurements with

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[1] Evaluated by visual inspection.

[2] Percentage by weight.

[3] Ethyl-methacrylate copolymer.

a PMT matched the expectation, however, if reasonable transport losses were assumed. Subsequent measurements of the photodiode showed limited angular acceptance which was not taken into account in the original measurement. A simulation of the setup including this effect produces consistent results between the PMT and photodiode measurements.

3. Glass housing

The quartz glass pressure housing has undergone static pressure testing up to 5250 psi (362 bar). After the test some optical defects were seen in the glass, but they may have been present prior to the testing. Repeated tests did not result in additional, or modified, glass features. No cracking was observed. Feedthrough connectors of the Seacon type previously employed in IceCube DOMs can be mounted on the quartz glass housing as needed.

We plan to structure the inside of the pressure vessel to further increase the efficiency. As the light passes from ice to quartz glass to air, it passes different refractive indices. As quartz glass has a greater refractive index than ice, nearly all the light passes through the first surface. Air has a lower refractive index therefore the light with angles $\theta \geq 48.75^\circ = \arcsin(\frac{n_{air}=1}{n_{ice}=1.33})$ does not enter the detector at the inner surface of the pressure vessel when the module is deployed in ice. This not only reduces the efficiency of the detector but also decreases the angular acceptance. In order to counteract both of these effects we investigate the use of lenticular lens arrays to cover the inside of the pressure vessel. A first calculation indicates that this can give an efficiency gain of up to 37%.

4. Conclusion and outlook

The WOM is a low cost, low noise and high efficiency optical module. It is mainly developed to be used in IceCube-Gen2 and similar large volume neutrino Cherenkov detectors. However the concept is flexible and can be adapted for other types of detectors like in the surrounding background tagger of the SHiP experiment [5]. For the realization of this detector a high efficiency WLS paint has been developed. It shifts light from the range of $250 - 400$ nm to > 400 nm. Efficiency measurements with PMTs showed capture and transport efficiencies of $\approx 50\%$ while photodiodes measurements show lower results. First simulations show consistency between both measurements when accounting for the photodiode's angular efficiency. An adiabatic light guide has been produced that acts as an adapter between the WLS tube and the small PMTs. The quartz glass pressure vessel in the necessary elongated shape has passed pressure testing. The assembly of a first complete prototype is progressing well, and gives hope that this novel concept can be tested in-situ soon.

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