Nuclear Instruments and Methods in Physics Research A261 (1987) 540–542
North-Holland, Amsterdam

A WAVESHIFTER LIGHT COLLECTOR FOR A WATER CHERENKOV DETECTOR

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Received 5 May 1987

A device has been developed which is capable of doubling the light collection capability of a 5 inch hemispherical photomultiplier tube. Known as a "waveshifter plate", its geometry is adaptable to various applications. Its marginal cost is small with respect to that of a phototube, it is readily removable, and it has minimum effect upon dark noise and timing resolution.

A device has been developed which is capable of doubling the photon collection of a 5 inch hemispherical photomultiplier tube (PMT). It can be adapted to match the geometrical specifications of any arrangement of hemispherical PMTs of arbitrary diameter. The device, a "waveshifter plate", consists of a 2 ft ×2 ft × 1/2 inch acrylic square doped at a concentration of 50 mg/l with bis-MSB [1] a waveshifting organic compound. As is shown in fig. 1, the PMT is springloaded against its plate with its bulb inserted in a tapered circular hole at the center. Plates enhance light collection by first absorbing photons which would otherwise fail to strike a PMT directly and then re-emitting light of a longer wavelength. Approximately 30% of the photons which the bis-MSB re-emits are trapped within their plate by total internal reflection at the acrylic–water interface. Since the plate is nearly transparent to the re-emitted light, some of the trapped light eventually reaches the photocathode and is recorded. Plate edges are buffed to a #6 polish, annealed, and covered with 2 mil. aluminized mylar [2] to better contain the light.

Bis-MSB is selected because its fluorescence properties satisfy two criteria. First, its absorption sensitivity is well-matched to the Cherenkov spectrum of relativistic particles in water. The left curve in fig. 2 shows the molar extinction coefficient $M(\lambda)$ as a function of incident wavelength λ. The absorption probability P_{abs} for a photon of wavelength λ is given by

$$P_{abs} = 1 - 10^{-ndM(\lambda)},$$

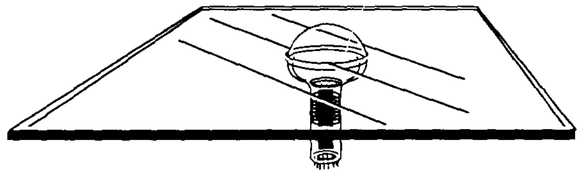

Fig. 1. Photomultiplier tube with waveshifter plate.

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(North-Holland Physics Publishing Division)

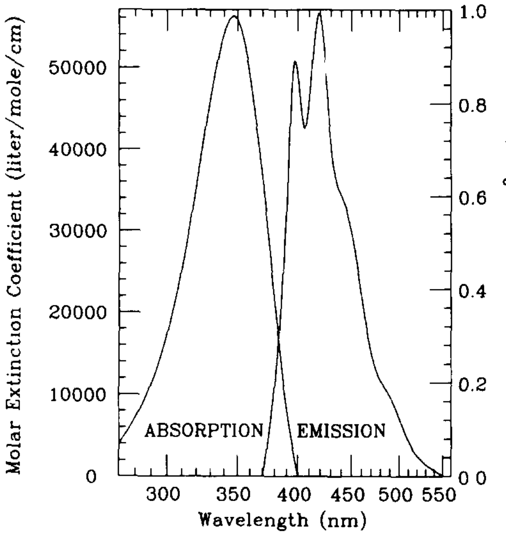

Fig. 2. Photon absorption and emission spectra of bis-MSB.

where n is the concentration of the fluorescent substance and d is the distance travelled through the plate. In this application, $n = 1.6 \times 10^{-4}$ mol/l and $d = 1.3$ cm for normally incident light; consequently, $P_{\text{abs}} \geq 0.95$ for 280 nm $\leq \lambda \leq$ 390 nm. The Cherenkov spectrum of light attenuated in 10 m of water is shown in fig. 3 for comparison. A significant fraction of the Cherenkov photons are within the plate's bandwidth of sensitivity.

Secondly, bis-MSB's spectrum of re-emitted light is well matched to the sensitivity of the bialkali photocathode. The right curve in fig. 2 shows the unnormalized re-emission probability as a function of re-emitted wavelength. It may be compared with fig. 4, the photocathode quantum efficiency. The good overlap between these two curves indicates that many trapped photons which reach the plate–bulb interface fire the PMT.

Tests of square plates ranging in size from 1 to 3 ft on a side indicate that light collection increases linearly with plate side length. The plate thickness and the concentration of the fluorescent compound are selected so that together they provide several absorption lengths of bis-MSB in the path of normally impinging light. The plate is mounted as far back on the PMT as possible to minimize the amount of photocathode which is blocked from direct photon hits and to maximize the area of plate–PMT interface.

Optical coupling between the plate and PMT is achieved without epoxy or other intermediate agent by milling the hole in the acrylic to match the bulb contour snugly. The lack of a coupling agent is dictated by the particular experiment for which these light collectors have thus far been employed. They are submerged in water which must remain ultrapure on a timescale of years, and the plates must be temporarily removed during maintenance periods once very several weeks. Tests made on plates sealed to PMTs with epoxy suggest that in applications where the use of epoxy is appropriate, it can raise the light collection capability by an additional 20%. Although flat-faced PMTs have not specifically been tested, it would seem that similar gains could be achieved by pressing them against the acrylic.

Studies of timing response show that for low light levels, PMTs with plates trigger on average 3 ns earlier

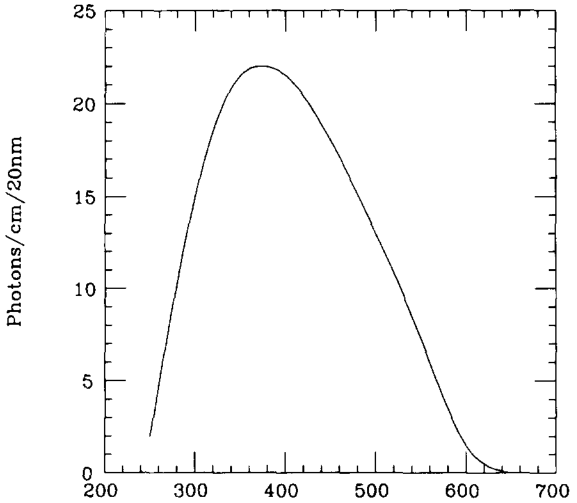

Fig. 3. The spectrum of Cherenkov photons which have travelled 10 m in water.

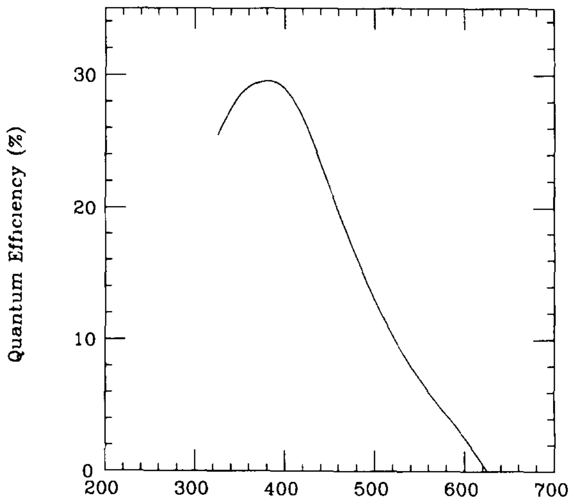

Fig. 4. Photomultiplier tube quantum efficiency vs wavelength.

than do PMTs without plates. The increased photoelectron production contributes to this via the "first photoelectron effect". As improved light collection increases the number of photoelectrons, the time of the earliest photoelectron, the one which determines the PMT trigger, systematically shifts. Furthermore, the plates stimulate photoelectrons from the perimeter of the photocathode. These pe's may have flight paths systematically shorter than those of photoelectrons emitted elsewhere on the bulb. Adjustment of the focussing electrodes may minimize the timing change. Plate addition degrades the timing resolution from 11 to 15 ns fwhm due to the increased pulse size, the added light path in the acrylic, and the finite decay time of the bis-MSB, 10 ns [4], which enter the width measurement in quadrature with the PMT jitter.

The increased photocurrent per incident photon increases the PMT afterpulse probability. Prepulse rate, due almost entirely to direct PMT hits, is unaffected by the plate.

In their present application, waveshifter plates increase the mean singles rate in the counters by about 2 kHz. Some other compounds which have fluorescence spectra comparable to those of bis-MSB (notably BBOT and BBQ) generate mean noise increases as small as 0.4–1 kHz, although the light collection enhancement which they achieve is only 70–80% of that reported here. Nevertheless, for low noise applications one of these compounds may be preferable.

Comparative measurements were made of the dark adaptation time of 20 PMTs with and without plates using a 17 day baseline. No difference was observed in the adaptation rates of the two sets; only the mean asymptotic noise values differed. This rules out the possibility of there being in the acrylic any compounds with long-lived metastable fluorescent states.

A higher noise rate when submerged in water than when operated in air suggests that the majority of plate-induced singles rate in the counters is caused by the PMTs' heightened sensitivity to low level radioactive decay products in the water. Since this noise increase is not a property of the plate itself, it may be avoidable in other applications of this device.

Acknowledgement

This work was supported in part by the US Department of Energy.

References

[1] Bis-MSB is a tradename for p-bis(0-methyl stryryl) benzene, $C_{24}H_{22}$.

[2] "Scotch" brand Number 850 polyester tape, manufactured by 3M, Inc.

[3] I.B. Berlmann, Handbook of Fluorescence Spectra of Aromatic Molecules, 2nd ed , (Academic Press, New York, 1971).

[4] Acrylic Plastic Scintillators for Large Area Applications, Polycast Technology Corp., Stamford, Conn. (1985).