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A method to enhance the sensitivity of photomultipliers for air Cherenkov telescopes

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Abstract

A simple method to enhance the sensitivity of photomultipliers (PMTs) will be described. The method is based on applying onto the cathode window a specially prepared lacquer containing a wavelength shifter (WLS). A rapidly evaporating lacquer solvent results in a milky surface that acts as a photon scatterer. Applying the method to the ET 9116A PMT (hemispherical borosilicate window and Rubidium-bialkali photocathode) resulted in a good sensitivity in the short-wave UV range as well as an $\gtrsim$20% increase above 330 nm. Details of the study, the procedure and a simple model for the explanation of the enhancement are presented.

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Keywords: Photomultipliers; Quantum efficiency; Wavelength shifter; Air Cherenkov Telescopes

1. Introduction

For fast photon detection with large-area sensors, PMTs are currently the most sensitive devices allowing for single photon counting with good time resolution. Typical quantum efficiency (QE) values are close to 25% in the spectral range between 350 and 450 nm. Extensions of the sensitivity below 300 nm requires quartz windows, while above 450 nm exotic cathode materials (like GaAs, GaAsP, etc.) are needed for high QE.

In many applications, an increase in QE is very desirable. A typical case is the use of PMTs in large Air Cherenkov Telescopes (ACT) for ground-based gamma-ray astronomy. In these detectors an enhancement of the sensitivity can be translated directly into a decrease in the energy threshold (E_{th}) of the telescope.

$$E_{\mathrm{th}} \propto \frac{1}{A_{\mathrm{mirror}} \times \mathrm{LCE}} \qquad (1)$$

where A_{mirror} is the area of the light collection reflector and LCE the light conversion efficiency of the entire system.

LCE is the product of the reflectivity of the mirror, the efficiency of the light guides and the detection efficiency (DE) of the photosensors. In

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the case of photomultipliers (PMTs), the DE is the product of the cathode QE and the collection efficiency (CE) of photoelectrons in the PMT front-end. LCE is wavelength dependent.

The original motivation for this study was the intention of lowering the threshold of the MAGIC telescope by increasing the sensitivity of the PMT camera.

MAGIC is a 17 m ∅ diameter ACT currently under construction on the Canary island of La Palma; the telescope will start taking data at the end of 2002.

In the MAGIC camera, the following type of PMTs are used: the 9116A and the 9117A from Electron Tubes, both with borosilicate hemispherical windows and Rubidium-bialkali photocathodes. The improvement in QE is achieved in part by extending the spectral sensitivity in the short-wave UV range by means of a wavelength shifter (WLS) and, on the other hand, by increasing the overall quantum efficiency (QE) by applying a layer of structured lacquer acting as a photon scatterer. In the following, we describe the method used.

2. QE enhancement by applying a special lacquer

2.1. Enhancement of the UV light sensitivity

At ground level, the observed Cherenkov photon spectrum from Cosmic Ray induced air showers extends down to 290 nm. The borosilicate window of the used PMTs have a spectral cut-off mid-point around 310 nm. We tried to enhance the UV sensitivity of the PMTs by coating them with a WLS that shifts the short-wavelength light to a longer wavelength where the photons can pass the window. A common procedure consists of depositing some fluorescent organic compound onto the glass window by evaporation. The drawback of this technique is that the coating has a very weak mechanical resistance, thus not being suitable for PMTs for an ACT. In addition, the method requires a vacuum-coating unit.

Another simple procedure (see Ref. [1]) consists of dissolving the WLS and some transparent plastic binder in an organic solvent. The window of the PMT is briefly dipped into this solution, and, after evaporation of the organic solvent, a layer of plastic binder and WLS is formed. The plastic binder has a good optical contact and a smooth surface with high internal light trapping. It was also found (see again Ref. [1]) that the WLS to binder ratio and the thickness of the layer were not critical for wavelengths above 220 nm.

Because of the spectral characteristics of the used PMTs and the Cherenkov photon spectrum from air showers, the WLS needs to absorb below ≈320 nm and to re-emit at the spectral range of maximum QE. An additional requirement is that the decay time of the WLS should be of the order of 1 ns, matching the time profile of typical Cherenkov light flashes from γ-induced showers.[1]

We have chosen 1.4 p-Terphenyl (PTP) as WLS and Paraloid-B72 [2] as binder. PTP absorbs light below 320 nm and re-emits it around 340 nm, where the QE of the used PMTs is about 90% of the peak value. The combination of PTP + Paraloid-B72 was measured to have a decay time of 0.9 ns (see Ref. [1]), matching our requirements.

Satisfactory results were obtained with a mixture of 0.5 g PTP and 2.0 g Paraloid-B72 (granulated plastic) dissolved in 50 ml Dichloromethane. The PMT (ET 9116A type) was dipped into this solution, leaving, after evaporation of the solvent, a very thin transparent layer of WLS and Paraloid. The gain in QE was measured as a function of wavelength by operating the PMT as a photocell (shortening all the dynodes and applying a voltage of 300 V between the photocathode and the dynode system). We used a spectrofluorometer[2] as light source and a calibrated PIN diode with quartz window.[3]

A large increase in sensitivity below 320 nm has been achieved, as shown in Fig. 1. The increase of the QE to only about 18% instead of 25% can be

[1] Fast response is mandatory for reducing the accidental trigger rates caused by the light of the night sky and for good gamma/hadron separation.

[2] The spectrofluorometer is a KONTRON INSTRUMENTS SFM 25 type from with a Xenon light source and a diffraction grating monochromator.

[3] As reference, a HAMAMATSU S1337-1010 BQ PIN diode has been used. Its radiant sensitivity was calibrated with an accuracy of 0.001 A/W in the range of 200−1200 nm.

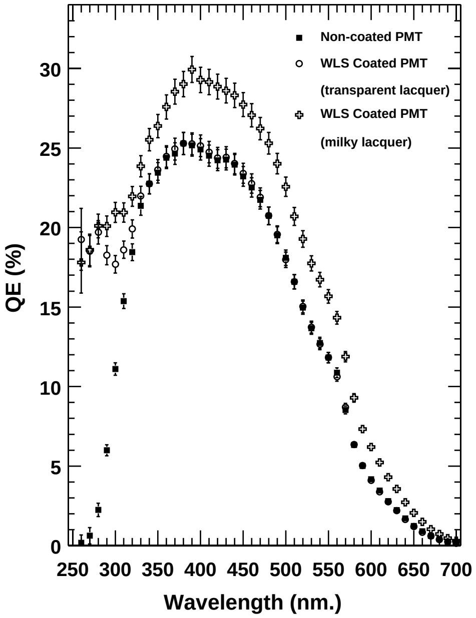

Fig. 1. Spectral increase in QE for coated PMTs (see text for further explanation).

explained partly by light losses due to isotropic emission (for $n = 1.5$ one expects 13% to escape into the air), a PTP QE somewhat below 100%, and the peak emission around 340 nm, i.e., where the intrinsic QE of the PMT cathode is around 22.5%.

2.2. *QE enhancement by means of a scattering layer*

In the process of liberating electrons from a PMT cathode, the photons have to be absorbed and the excited electrons must reach the vacuum interface with an energy exceeding the work function (W_{th}) of the cathode material (close to 2 eV for Cs and Rb) to be able to escape. In such a simplified model,

$$QE \propto P^{ph}_{abs} \times P^{e-}_{esc} \tag{2}$$

where P^{ph}_{abs} is the probability for a photon to be absorbed and P^{e-}_{esc} the probability for the photo-electron to escape the photocathode.

The photon absorption probability depends on the wavelength and path length inside the cathode, while the escape probability depends on the pe energy and its distance from the vacuum interface (in reality, the process is much more complex and we refer the interested reader to the relevant literature).

The longer the trajectory of the photon through the photocathode, the higher is the probability to excite an electron. On the other hand, the longer the distance the pe has to travel inside the cathode material, the lower is the escape probability. Because of these two counteracting effects, there exists an optimum cathode thickness that maximizes the QE for a given wavelength.

Note that the sensitivity should increase by increasing the path length of the photons inside the PMT cathode if one manages not to increase the path length for the excited electrons. This is the reason for the enhancement in the QE of a PMT when the light enters the photocathode with a large angle (see Ref. [3]).

There are companies that (on special order only) treat the window of some of their PMTs to scatter the incoming photons, thus increasing their incident angles in the photocathode (like the PMT model type 9829 from Electron Tubes). The improvement achieved in the QE is about 7% at 400 nm and 16% at 600 nm.[4] A larger enhancement for long wavelengths is expected due to the fact that the absorption coefficient of the photons inside the PMT cathode decreases when lowering the energy of the photons. An important drawback of this technique is that it is difficult to keep the window of these photomultipliers clean. Traces of dirt or grease deposited on the glass are difficult to remove.

During our studies, we found out more or less by chance that a frosted lacquer layer resulted in a sizeable increase in QE and also in the spectral range where the WLS is not functioning. The formation of the frosted (milky) surface is the result of a rapid evaporation of the used solvent.

While the above-noted mixture of PTP and Paraloid-B72 produced a clear surface, the doubling of Paraloid-B72 concentration resulted in the formation of a milky surface. Dipping the PMT

[4] Private communication: R M McAlpine from Electron Tubes Inc.

several times (2–3 times) with interruptions of a few minutes resulted in a layer that was no more transparent. The increase in sensitivity was well above the one quoted by industry (see Fig. 1), but this effect could be traced at least partly to the hemispherical shape of the used PMTs.

We conducted a series of tests to find the composition of PTP, Paraloid and Dichloromethane that optimizes this scattering effect. We varied the concentration of Paraloid from 1 to 10 g for a fixed quantity of 0.5 g PTP in 50 ml Dichloromethane.[5] It was found that the concentration of Paraloid is not critical provided it is above 3 g/50 ml solvent. Once the frosted layer is formed, no difference in sensitivity (within the errors of our measurements) was found for different Paraloid concentrations. Only when $\geqslant$10 g of Paraloid was used, a slight reduction in the short-wave UV sensitivity was observed. We attribute this reduction to the UV absorption of the binder.

We also changed the concentration of PTP from 0.0 to 0.5 g (in steps of 0.1 g) dissolved in 50 ml Dichloromethane and 5 g Paraloid. By adding the WLS, we found no significant improvement for wavelengths above 330 nm.

It was found that a higher admixture of PTP results in a faster and easier formation of the milky layer (the PTP acts apparently as a 'seed'). Using only Paraloid, it is necessary to speed up the evaporation rate of the solvent to form a good 'scattering' layer. This could be achieved by shaking the PMT very fast right after taking it out of the solution. (For slow evaporation of the solvent, the deposited layer on the glass is rather transparent.) Actually, if Toluene instead of Dichloromethane is used as a solvent, it is not possible to obtain a milky surface, regardless of the used quantity of PTP and the number of times the PMT is dipped into the solution. This can be explained by the difference of vapor pressure at room temperature. The boiling point of Toluene is 111°C whereas that of Dichloromethane is 40°C.

The uniformity in the response has been tested for some treated PMTs and it was found that it improves with respect to the one of the plain PMTs. The non-uniformities of the untreated PMTs are slightly reduced by the scattering of the photons in the PMT front-end.

[5]The WLS layer can be removed easily by wiping the PMT window with a tissue soaked in alcohol or acetone.

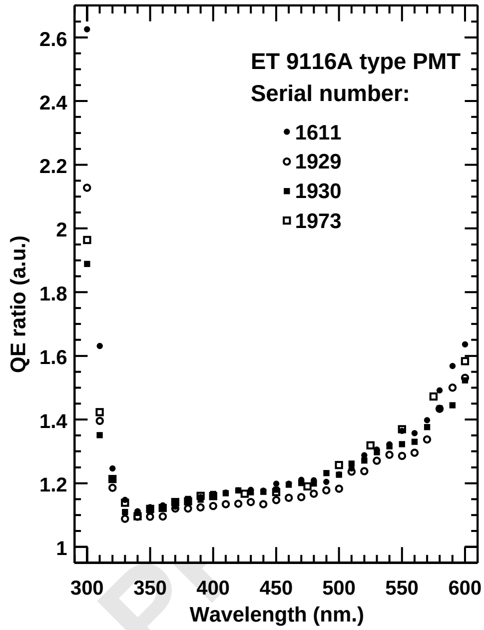

Fig. 2. QE enhancement observed in four coated PMTs ET 9116A.

In order to check the reproducibility of the procedure, several PMTs were coated with the 'standard mixture' of 0.5 g PTP, 5 g Paraloid-B72 and 50 ml Dichloromethane. The improvement in the QE is shown in Fig. 2 as a function of wavelength (data below 300 nm are omitted for clarity). We found a consistent improvement in the QE.

We also tested the above-described procedure on a flat window bialkali PMT, the 19 mm ∅ HAMAMATSU R750, and we observed also an increase in the QE, but not as high as for the hemispherical PMTs. At 400 nm, the increase was close to 8% and at 600 nm around 19%.

A simple model for explaining the enhancement achieved in the QE above 330 nm is sketched in Fig. 3. Compared to the plain PMT the amount of the reflected light is larger due to the diffuse layer, thus decreasing the number of photons impinging onto the cathode. On the other hand, there are

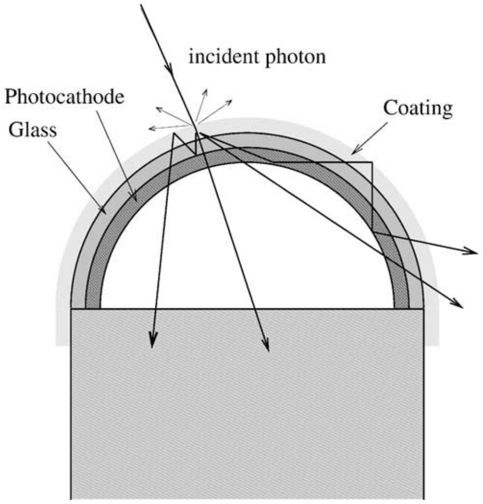

Fig. 3. Scattered photon trajectories in a hemispherical window PMT.

several effects related to the scattering of the photons that contribute to a significant increase in the QE. Some scattered photons enter the photocathode with a large angle; therefore, they have a higher probability of being converted. Others are deflected in such a way that, due to the true hemispherical shape of the photocathode, their trajectories cross the photocathode twice ("double crossing"), thus having an even higher probability of being absorbed. Some other photons may be scattered such that they get trapped in the glass window, having many chances of exciting an electron.

There exists another effect which should partly be responsible for the increase in QE. The amount of light reflected by the photocathode is by no means negligible. The reflectivity increases with wavelength and can reach 30% at 600 nm (see Ref. [4]). A fraction of this light will be reflected back to the photocathode by the scattering layer, thus adding to the production of photoelectrons.

All these explanations are in agreement with the observation that, above 330 nm, the increase in the QE is larger for longer wavelength (see Figs. 1 and 2). Below 330 nm down to 260 nm, the QE enhancement increases mainly due to the action of the WLS.

3. Estimation of the gain in detection efficiency for a Cherenkov Telescope at 2200 m. a.s.l

In ACTs, the detection efficiency increases in first order proportionally with the increase in the number of detected photoelectrons. In order to calculate this increase, one needs to fold the improved QE (λ) of the PMTs[6] with the photon spectrum expected at 2200 m. a.s.l. For this estimate, we simulated gamma-ray showers in the 10 GeV$-$30 TeV energy range with a spectral index of -2.6 at 0, 20, 40 and 60° Zenith Angle (ZA) using the program *CORSIKA* 6.005 (see Ref. [5]). For each ZA, 10^6 photons reaching the telescope were stored in a histogram spanning 290$-$600 nm in 5 nm bins. The normalized spectral photon intensity is shown in Fig. 4. The cut-off for UV light below 290 nm by Ozone absorption is well visible. The spectrum is also strongly affected by Rayleigh and Mie scattering. Note that at 0° ZA, the maximum number of photons occurs for $\lambda \sim 335$ nm, whereas at 60° ZA, due to the longer path of the photons in the atmosphere, the maximum is shifted to $\lambda \sim 400$ nm.

Folding the photon spectrum, at a given ZA, with the QE (λ) of the PMT one can compute the mean quantum efficiency ($\langle \mathrm{QE} \rangle$) for that ZA:

$$\langle \mathrm{QE(ZA)} \rangle = \frac{N_{\mathrm{phe}}(\mathrm{ZA})}{N_{\mathrm{ph}}} = \frac{\int \mathrm{QE}(\lambda) N_{\mathrm{ph}}(\mathrm{ZA}, \lambda)\,\mathrm{d}\lambda}{\int N_{\mathrm{ph}}(\mathrm{ZA}, \lambda)\,\mathrm{d}\lambda} \quad (3)$$

with $N_{\mathrm{ph}}(\mathrm{ZA})$ being the total number of photons impinging onto the PMTs and $N_{\mathrm{phe}}(\mathrm{ZA})$ being the total number of photoelectrons produced at the simulated ZAs. Comparing the results for the $\langle \mathrm{QE} \rangle$ of the PMT before and after applying the lacquer, one can calculate the increase in the detection efficiency. The results are summarized in Table 1.

Note that the enhancement in $\langle \mathrm{QE} \rangle$ does not change very much with ZA.

According to Eq. (1), the use of this technique to enhance the QE has the same effect on the E_{th} of an ACT as an increase of the area of the light

[6] It is assumed that the CE of the coated PMT is not altered significantly compared to that of a plain PMT.

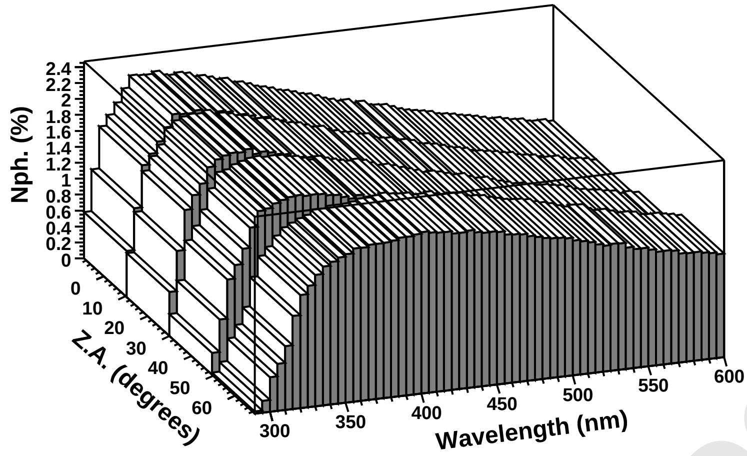

Fig. 4. Photon spectrum at 2200 a.s.l. for 0°, 20°, 40°, 60° ZA.

Table 1
Increase in the ⟨QE⟩ at 2200 m. a.s.l.

ZA (deg)	⟨QE⟩ (%)	⟨QE⟩ after coating (%)	Relative increase (%)
0	19.6	23.7	21.3
20	19.6	23.7	21.2
40	19.6	23.6	20.8
60	19.5	23.4	20.5

collection reflector by about 20%. Obviously, any enlargement of the reflector of the telescope would be much more expensive and would introduce additional problems related to the increase in the inertia of the telescope.

For the above-quoted estimates, we have neglected the angular and cathode non-uniformity of the PMTs, the wavelength dependence of the reflectivity of the mirrors and the influence of the light of the night sky (LONS). Calculations are ongoing to estimate the impact of these effects.

4. Additional QE increase by a proper design of the light collectors

Light collectors in front of the camera PMTs are needed to minimize the light losses due to dead areas between PMTs and also to reject the background light outside the aperture defined by the reflector of the telescope. The combination of a properly designed light collector and a hemispherical window photomultiplier allows that, many Cherenkov photon trajectories cross the photocathode twice (“double crossing photons”), thus increasing the net QE of the PMT up to ~20–25% (see Refs. [6,7]).

We found that for coated PMTs the additional increase in QE by “double crossing photons” is nearly halved compared to that of the plain ones (see Fig. 5). The reason is that the additional increase comes mainly from those photons which were not strongly scattered when passing the milky layer. It must be pointed out that, despite being reduced in number, these photons have a higher probability of producing a phe; if they are not converted in the second hit, they still may be reflected back in the frosted layer, thus having another (and even two more) chance(s) of producing a phe.

In summary, by coating our PMTs and allowing the incident photon trajectory to cross the photocathode twice, we obtain a QE increase which is more than ~30% for wavelengths above 330 nm. However, we would like to point out that the real increase in the DE might be lower due to the poor CE of these PMTs very close to the edge of the photocathode (see Refs. [6,7]). This possible reduction needs further studies.

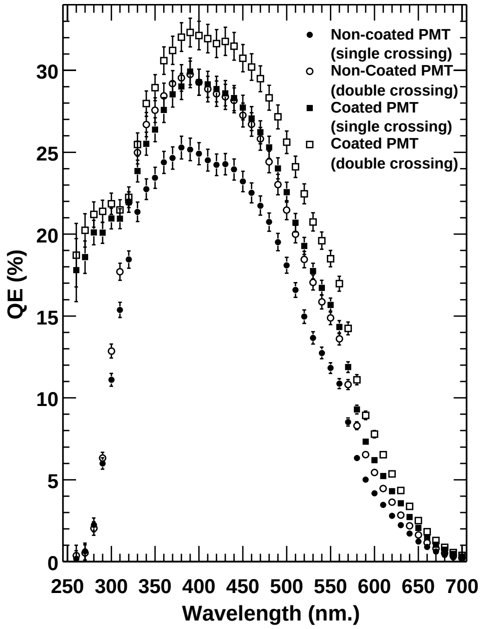

Fig. 5. Enhancement of the QE for different configurations of surface treatment and incident photon trajectories crossing the photocathodes once or twice.

5. Conclusions

We presented a simple method to enhance substantially the QE(λ) of a PMT. A lacquer consisting of a WLS, a plastic binder and a rapidly evaporating solvent results in a milky layer that scatters the photons thus increasing their probability of producing phe. In the particular case of the ET 9116A and 9117A PMTs (hemispherical borosilicate window and Rubidium-bialkali photocathode) used in the MAGIC telescope, this technique results in an increase in the detection efficiency (DE) of more than 20%. An additional increase in the DE is obtained by using light collectors that make about half of the incident photon trajectories to cross the photocathode twice.

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