IMPROVED YIELD OF PHOTOMULTIPLIERS FOR CHERENKOV LIGHT

P. J. CARLSON

CERN, Geneva, Switzerland

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The combined effects of using a wavelength shifter and higher voltage for better photoelectron collection is shown to give a gain of 70% in the photo-electron yield for the 11 cm diameter phototube RCA 8854 in a typical Cherenkov counter.

1. Introduction

In a Cherenkov counter, the number n_e of detected photoelectrons is given by¹⁾

$$n_e = N_0 L \sin^2 \theta, \quad (1)$$

where N_0 is a parameter characterizing the photomultiplier and the optical collection efficiency of the counter, L is the radiator length, and θ is the Cherenkov angle.

High values of the constant N_0 have been obtained for some 5 cm diameter photomultipliers equipped with a bialkali photocathode and with a fused silica entrance window. The RCA 31000 M has given N_0 in the range 140–170 cm⁻¹, and the 56 DUVF 100 cm⁻¹^{2,3)}. The 11 cm diameter photomultipliers with bialkali cathodes are not as yet available with a fused silica entrance window. The corresponding values of N_0 are lower, in the range 50–80 cm⁻¹^{4,5)}. Earlier measurements made on tubes with a CsSb cathode gave values also in the range 50–80 cm⁻¹⁶⁾.

With the new high-energy accelerators providing secondary particle beams with momenta of 100 GeV/c or more, the desired threshold for Cherenkov light is raised. As an example, pure He has a threshold for pions of about 15 GeV/c at atmospheric pressure. With $N_0 = 100$ cm⁻¹, about 0.6 photoelectron per metre of radiator can be expected. However, to get sufficient statistics, the counters become bulky.

Recently, much interest has been devoted to increasing N_0 , thereby effectively reducing the radiator length L . One way of doing this has been to use wavelength shifters to make use of that part of the spectrum which is cut off by the photomultiplier windows. Recent work is described in the articles of Garwin et al.⁷⁾, Baillon et al.⁸⁾, and Krieder et al.⁹⁾. Another way has been to enhance the effective quantum efficiency of the photomul-

tiplier tube by optimizing the collection of the photoelectrons from the photocathode. The variation of the collection efficiency with the voltage, between the cathode and the first dynode, was clearly demonstrated for photocathodes of the older S-11 type (CsSb) in the work of Duteil et al.⁶⁾. In a recent work, Lorentz¹⁰⁾ has measured the variation of the quantum efficiency with the voltage, between the cathode and the first dynode, for modern tubes such as the RCA 8854, 58 DVP, and XP 2041, equipped with bialkali (K₂CsSb) cathodes.

In this work the combined effects of a wavelength shifter evaporated on the tube and a variation of the focusing voltage have been tried in a Cherenkov counter. The phototubes were 11 cm diameter tubes, RCA 8854 and 58 DVP.

2. Experimental method

The Cherenkov light produced by 2 GeV/c electrons in N₂ at atmospheric pressure was detected by a photomultiplier in a set-up shown in fig. 1. The radiator length chosen was quite short, 0.67 m, to ensure that all Cherenkov light (the Cherenkov angle is 24 mrad) hit the photomultiplier.

In this set-up the mirror had a reflectance of

Fig. 1. Experimental layout. The beam enters from the left. S₁ and S₂ are scintillators; C₁ and C₂ are beam Cherenkov counters, both filled with CO₂. C is the test counter, filled with N₂.

50% at 190 nm rising to a constant value of about 85% for wavelengths longer than about 240 nm. Small glass mirrors can be made with a reflectance extending much further into the UV part of the spectrum (see, for example, ref. 3). The conditions of this experiment should, however, resemble those where large curved mirrors made with a plastic backing were used, but for which it seems very difficult to get a good reflectance below 200 nm.

The incident electron was defined by the two scintillators S_1 and S_2 and by the two Cherenkov counters $\check{C}_1$ and $\check{C}_2$, both 1 m long and filled with CO_2 at 2 atm. The particle flux at 2 GeV/c, with $\Delta p/p = \pm 1\%$, was typically 100 electrons ($S_1 \cdot S_2 \cdot \check{C}_1 \cdot \check{C}_2$) per machine burst. For the calculation of the number of photoelectrons, the purity of the electron beam is essential. The lead-glass block downstream from the S_2 counter permitted a detailed study of the electron beam, and in fig.

Fig. 2. Pulse-height spectrum obtained in the downstream lead-glass block (see fig. 1) for the electron beam. With a π trigger, the peak appears at the position marked "hadron peak".

Electronics lay-out.

Fig. 3. Electronics layout.

2 a pulse-height spectrum is displayed. We estimate a background in the electron sample of 1% (corresponding to a π rejection of 10^{-4}).

The electronics layout is shown in fig. 3. For the RCA 8854 tube, the pulse-height spectrum was analysed to give n_e . This was possible because these tubes have a high-gain (~ 25) first dynode permitting the direct observation, on a pulse-height analyser, of peaks corresponding to 1–4 photoelectrons¹¹).

We also estimated n_e from the inefficiency of the test counter, which is $\exp(-n_e)$. The two methods gave, within errors, the same result for n_e . For the 58 DVP tube, which has a conventional first dynode that does not permit the direct observation of peaks corresponding to 1–4 photoelectrons, n_e was estimated from the inefficiency only.

The photomultiplier chain used for the

Fig. 4. The photomultiplier chain used for the RCA 8854 potential divider. The resistance R could be changed in order to change V_{dyn} , the voltage across the cathode to the first dynode.

RCA 8854 is shown in fig. 4. It corresponds to the one recommended by RCA, with the exception that the voltage across the photocathode to the first dynode (V_{dyn} in fig. 4) could be varied by varying the resistance R and the over-all voltage V_0 . For the 58 DVP the conventional Philips type-A chain was used.

For the RCA tube several different thicknesses of evaporated wavelength shifter were used. The voltage V_{dyn} was varied. The 58 DVP was tried with and without the wavelength shifter.

3. The wavelength shifter

Many types of wavelength shifters have been investigated^{7-9,12-13}). We have used paraterphenyl (PT) (1, 1'; 4', 1'' terphenyl) because it has a short decay time (1 ns), is more stable than tetraphenylbutadiene (TPB)¹⁴), and has a high conversion efficiency. The absorption¹⁴) in a layer of PT as a function of the wavelength λ is shown in fig. 5 for different layer thicknesses. The dip in the absorption for $\lambda = 235$ nm, important for thicknesses less than about 1000 nm, is less pronounced for other configurations of the three rings in terphenyl. However, both (1, 1'; 2', 1'') and (1, 1'; 3', 1'') terphenyl has substantially larger decay times¹⁴), and for this reason it cannot be used. The emission spectrum for PT is peaked at 360 nm with a fwhm of about 80 nm. In fig. 5 is also displayed (dashed curves) the transmission of the photomul-

Fig. 5. The absorption in a layer of paraterphenyl as a function of the wavelength. Different curves correspond to different layer thicknesses, given in the figure in nm. The dashed curves give the transmission through photomultiplier windows: "Corning 9741", 1.9 mm (a, used for RCA 8854) and borosilicate 3 mm (b, used for the 58 DVP).

tiplier windows* for the RCA 8854 (curve a) and for the 58 DVP (curve b).

Brunet et al.¹³) give the maximum fluorescence yield for a thickness of 0.8 mg/cm² (8000 nm). Garwin et al.⁷), taking into account the absorption of light with longer wavelengths, give a maximum yield for a thickness of 0.2–0.3 mg/cm² (2000–3000 nm). Baillon et al.⁸) have tried several thicknesses and give a constant gain for thicknesses 0.02–0.2 mg/cm² (200–2000 nm).

For this test we tried thicknesses of 100, 200, 500, 1000, and 3000 nm of PT. The coating was put on the photomultiplier window by evaporation under vacuum, with an evaporation time of 3–4 min.

4. Results

4.1. LAYER THICKNESS OF THE WAVELENGTH SHIFTER

Of the thicknesses tried (100, 200, 500, 1000, and 3000 nm), the maximum gain was obtained for thicknesses in the range 200–1000 nm, the 100 nm and 3000 nm ones giving a reduction of about 20%. For the remaining tests, 1000 nm was adopted as standard, both for the RCA 8854 and the 58 DVP.

4.2. YIELD OF THE RCA 8854

The results are summarized in fig. 6, where n_e is shown as a function of V_{dyn} . Using a coated tube, there is a net gain of about 40%; this gain

* Manufacturers data are: for RCA 8854, (1.9 ± 0.4) mm Corning 9741 glass; and for 58 DVP, 3 mm borosilicate glass.

Fig. 6. The yield of photoelectrons (n_e) in a radiator length of 0.67 m as a function of V_{dyn} , the voltage across the cathode to the first dynode for the tube RCA 8856. Also shown is the over-all tube voltage V_0 . The vertical scale to the right gives the constant N_0 in eq. (1). The coating was 1000 nm paraterphenyl.

Fig. 7. The ratio $k = n_e$ (coated tube)/ n_e (uncoated tube) for the RCA 8854 as a function of V_{dyn} .

is independent of V_{dyn} , as shown in fig. 7. The gain of 40% agrees with the results of Baillon et al.⁸⁾.

A substantial gain can also be obtained by increasing V_{dyn} , in agreement with the results of Lorenz¹⁰⁾. The recommended value given by RCA is 670 V. By running the tube with 1000 V between the cathode and first dynode, the gain is about 25%. The over-all gain, using both the wavelength shifter and $V_{\text{dyn}} = 1$ kV, will amount to about 70%. The tube can be operated with even higher values of V_{dyn} , apparently without reducing its lifetime¹⁰⁾.

In fig. 6 is also given the corresponding value of the constant N_0 in eq. (1). Notice that this N_0 scale includes the effect of the mirror.

An increase in the yield of detected photoelectrons with increasing V_{dyn} is expected from the energy distribution of the photoelectrons from the K_2CsSb photocathode (bialkali). This distribution has been measured by Nathan et al.¹⁵⁾ for photon energies in the range 2–5 eV (240–600 nm); their results are shown in fig. 8. For longer wavelengths, 400–600 nm, there is a well-defined peak at around 1 eV. For shorter wavelengths, down to 240 nm, a broader spectrum extending up to 4 eV kinetic energy is obtained. Since the photoelectrons are emitted almost isotropically, a higher value of V_{dyn} will focus more of the high-energy photoelectrons to the first dynode.

4.3. YIELD OF THE 58 DVP

With 2.6 kV operating voltage, the uncoated tube gave $n_e = 1.6$, and with 1000 nm of PT it gave $n_e = 3.5$. The gain is 2.2. Baillon et al.⁸⁾ obtained an even higher gain with a similar tube but with a different photocathode, the S-11. The new 58 DVP, which has a window that transmits more UV, seems to give a gain of 1.7 under similar conditions¹⁶⁾.

Fig. 8. The distribution of photoelectron kinetic energy for different incident photon energies for the bialkali photocathode. Data from Nathan et al.¹⁵⁾.

5. Calculated response of the photomultiplier

The number of photons per wavelength interval is given by¹⁾

$$\frac{dN_y}{d\lambda} = \frac{2\pi L}{137} \sin^2 \theta \frac{1}{\lambda^2} = \frac{2\pi L}{137} \left(1 - \frac{1}{n^2 \beta^2}\right) \frac{1}{\lambda^2}, \quad (2)$$

where L is the radiator length, θ the Cherenkov angle, n the refractive index of the medium, βc the particle velocity, and λ the wavelength of the emitted radiation. The number of detected photoelectrons in the photomultiplier will be

$$n_e = \frac{2\pi L \sin^2 \theta}{137} \int_{\lambda_1}^{\lambda_2} \frac{d\lambda}{\lambda^2} T(\lambda) R(\lambda) \times \\ \times \{q(\lambda) [1 - A(\lambda)] + q_e f A(\lambda)\}. \quad (3)$$

Here

$T(\lambda)$ is the transmission of the radiating medium, $R(\lambda)$ is the photon collection efficiency,

$q(\lambda)$ is the effective quantum efficiency of the photocathode,

$A(\lambda)$ is the absorption in the layer of wavelength shifter on the glass window of the phototube,

q_e is the quantum efficiency for a photon, emitted from the wavelength shifter, that hits the photocathode,

f is the probability that a photon absorbed by the wavelength shifter causes a shifted photon to hit the photocathode.

We set $T(\lambda) = 1$ (N_2 is transparent down to 150 nm). For $R(\lambda)$ we use the measured value of the reflectance, 88% down to $\lambda = 250$ nm; $R(\lambda)$ then decreases rapidly, passing 50% at 190 nm. Below 160 nm, $R = 0$. The effective quantum efficiency $q(\lambda)$ is more difficult to get. It is well known that the manufacturers data are in general

Fig. 9. The quantum efficiency for the bialkali photocathode as a function of the wavelength λ . Curve (a) represents manufacturers data (RCA 8854). Curve (b) represents the effective quantum efficiency for the RCA 8854 with about 900 V between the cathode and the first dynode (see text). Curve (c) represents the data of Sobieski¹⁷).

too high⁶) because the collection efficiency is not taken into account. In fig. 9 we illustrate this for the RCA 8854. Curve (a) represents manufacturers data, reaching a maximum quantum efficiency of almost 30% for $\lambda = 340$ nm. Curve (b) represents the effective quantum efficiency used in our calculation. It has been deduced from the work of Lorenz¹⁰) and Sobieski¹⁷), taking into account the transmission through the photomultiplier window (see fig. 5) and assuming a tension of 900 V between the cathode and the first dynode. Sobieski's data, representing the quantum efficiency without any window, are shown as curve (c). The absorption $A(\lambda)$ is taken from fig. 5. The quantum efficiency for the 360 nm photon from PT is set to $q_e = 14\%$. Finally, the factor f is taken to be $f = 0.74$ ⁸).

The results of the integration are compared with the measured values of n_e in table 1. For the 58 DVP we used the same parameters as for the RCA 8854, with the exception of $q(\lambda)$ which was modified for $\lambda < 340$ nm to take into account the transmission of the borosilicate window, which is 50% for $\lambda = 310$ nm. The photocathode material is the same as that for the RCA tube.

The calculated values are 15–20% too high for the RCA tube and 30–35% too high for the DVP. For the RCA 8854 the measured ratio k , with and without the wavelength shifter, is 1.41 ± 0.04 (fig. 5). The calculated value, $k = 1.47$, is consistent with the measured one. The calculated value of k depends critically on the assumption that the wavelength shifter absorbs all light with

TABLE 1

Calculated and measured number of photoelectrons. The radiator length, L in eq. (3), is 0.67 m, and the radiator N_2 has $\sin^2 \theta = 5.4 \times 10^{-4}$.

Tube ^a	Wavelength shifter (nm)	Number of photoelectrons (n_e) calculated from eq. (3)	measured
RCA 8854 ^b	0	3.7	3.2
RCA 8854 ^b	1000	5.4	4.4
58 DVP	0	2.4	1.6
58 DVP	1000	5.4	3.5

^a RCA 8854, serial 16753, 58 DVP serial 5867.

^b We give here the results for a voltage of about 900 V between the cathode and the first dynode.

wavelengths below 300 nm. To the best of our knowledge the absorption has not been measured below 200 nm¹⁴). Assuming, for instance, that there is no absorption below $\lambda = 185$ nm, this brings the ratio from $k = 1.47$ to $k = 1.37$. For the 58 DVP, the measured and calculated values also agree, being $k = 2.2$.

The uncertainty in R and q can well explain the 15–20% loss for the RCA tube. For the DVP there seems to be an over-all lower value of the effective quantum efficiency, indicating a poorer collection. This agrees with the conclusion of Lorenz¹⁰). Duteil et al.⁶) give effective quantum efficiencies for some 5 cm diameter tubes (56 AVP, 56 DVP and 56 UVP) of 11–15% around 400 nm, similar to the values obtained for the 11 cm tubes.

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