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R/P091

absolute calibration of photomultiplier based detectors - difficulties and uncertainties

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abstract

Photomultiplier manufacturers can provide a calibration of quantum efficiency over a range of wavelengths with an accuracy of up to 2%. To convert these figures to absolute counting efficiency requires knowledge of photomultplier collection efficiency, F. Traditional methods of or determining F are discussed with emphasis on sources of error. Light sources emitting at a known photon rate allow the absolute quantum efficiency to be determined directly. It is important in all attempts at absolute calibration to appreciate the conditions which manufacturers apply when calibrating photomultipliers.

1 introduction

It is often a requirement in the planning and modelling stages of an experiment, involving the detection of low light levels, to be able to assign a photon detection efficiency to each photomultiplier. Subsequently, in the analysis of experimental results it may be desirable to characterise each event in terms of the number of photons emitted at the source. This is particularly relevant in the fields of high-energy physis and astrophysics to the class of detectors based on the RICH prinicple; massive water Cherenkov or scintillation tanks and large aperture air shower telescopes. Naively, it may appear that making absolute measurements of light signals only requires a photomultiplier with calibrated photosensitivity of known accuracy. Obtaining such a device presents the first difficulty: manufacturers and standards laboratories do not provide photomultipliers calibrated in a manner relating to their actual mode of operation. For practial purposes the collection efficiency, F, of the multiplier must be known in order to translate quoted photosensitivity to what may be called absolute quantum efficiency. Alternatively one may calibrate a photomultiplier by using a photon source of known emission characteristics, in which case a knowledge of F and quantum efficiency is not required. Whatever method is used it is important to calibrate a photomultiplier in a manner that is compatible with its actual mode of operation.

2 spectral response calibration (quantum efficiency, η)

Light detectors may be calibrated in two ways. Either, by reference to a calibrated photocell or by using a calibrated light source. At Electron Tubes we use a photocell calibrated by the National Physical Laboratory (NPL) in England. The photocell is a 52 mm, 9659Q, photomultiplier which is calibrated as a vacuum photodiode – that is, all dynodes, focusing elements and the anode form a common collector. The beam of radiation is incident with its axis normal to the photomultiplier window to within 1° irradiating a circular, concentric region of diameter 25 ± 5 mm. The reason for stating the measurment conditions and the choice of unity gain will become obvious later in this paper. The accuracy of η, to 2σ, quoted by the standards laboratory depends on the wavelength of interest and the relative spectral sensitivity: it ranges between 3 and 1% over the range 200 nm $\leqslant \lambda <$ 390 nm and ~ 0.5% for 390 nm $\leqslant \lambda <$ 680 nm. The quoted uncertainty increases rapidly beyond 680 nm primarily because the sensitivity itself is rapidly decreasing for this photocathode type. More details on optical radiation measurements and a review of the subject may be found in Ref. [1]. Of course a calibiration offered by ETL will be degraded by systematic errors introduced by our test equipment but we can provide data with an estimated uncertainty of 3% (2σ) for light wavelength 300-700 nm.

Calibrated silicon photodiodes offering high sensitivity in the infra-red region of the spectrum, together with very wide dynamic range have recently been used for photomultiplier calibration [2, 3].

The alternative to a calibrated detector is a light source calibrated for absolute spectral radiance as used by Besson et al., for example [4]. As for a detector the results only apply subject to meeting the calibration conditions.

3 photomultiplier collection efficiency, F

As stated in Section 2 all manufactuers quote quantum efficiencies for photomultipliers under diode operation whereas users want information for photomultiplier operation. The absolute quantum efficiency of a photomultiplier is always less than that based on the assumed photocathode quantum efficiency. This is because a proportion of photoelectrons are lost after emission from the photocathode, as illustrated for several sample trajectories shown in an electron-optics simulation

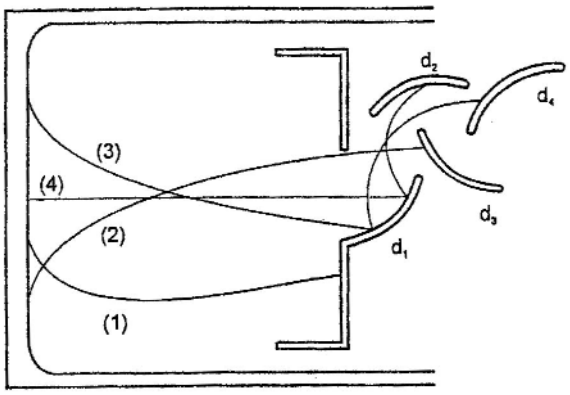

figure 1 electron optics of a photomultiplier front-end showing how photoelectrons get lost.

of **figure 1**. The photoelectron following tragectory (1) does not propagate since it strikes the support structure for d_1; (2) misses d_1 hitting the back of d_3; (3) produces secondary electrons, one of which skips d_2 and d_3 landing on the back of d_4 resulting in an undersized output and (4) is an example of ideal detection where the photoelectron lands in the centre of d_1.

Currently available electron-optical programmes provide Monte Carl simulations of front-end photoelectron trajectories which predict F values between 70 and 95% for a range of photomultiplier sizes. Simulations serve as a useful design tool but ultimately experimental confirmation of F is required. Clearly if F is known then manufacturer's quantum efficiency data may be scaled to provide the required absolute efficiency of the photomultiplier.

Photomultiplier applications fall into three categories: single photon detection; light pulses containing multiple photons and direct current measurements (electometer). Two definitions of $F$are required to cover these three operational modes. Both definitions of F involve gain and it is important to distinguish between photomultiplier gain $<G>$ and multiplier gain $<g>$. The mean gain $<G>$ of a photomultiplier is defined as the ratio of the anode current to the cathode current. The mean multiplier gain $<g>$ is the mean anode charge, produced by a single photoelectron, divided by the electronic charge, e.

Referring to single photon detection, F may be defined as

$$F_1 = \frac{\text{number of pulses detected at the anode}}{\text{number of electrons leaving the cathode}}$$

$$= n_a/n_k = n_a/(I_k/e) \qquad \ldots(1)$$

where I_k is the photocurrent, which can be measured.

The definition in equation **(1)** can be extend to cover multiple photon dtection and for DC detection F is simply

$$F_2 = \frac{\text{photomultiplier gain}}{\text{multiplier gain}} = <G>/<g> \qquad \ldots(2)$$

4 practical consideration in the determination of F_1 andF_2

Referring to equation **(1)**, counting the number of anode pulses above a fixed threshold poses no experimental difficulties. However, bearing in mind that photon counting is a low light level application, it is readily shown that relatively high count rates such as 6 x 10^6 s^{-1} at a gain of 10^7 correspond to cathode currents of the order of 10^{-12} amps.

Reliable determination of F by this method is compromised by the difficulty in measuring low cathode currents – even measuring cathode currents of the order of 10^{-11} A presents a considerable experimental challenge for any photomultiplier [5]. In principle this difficulty can be overcome by using neutral density filters, either of assumed attenuation coefficient, α, or better by actually measuring α *in* situ. The method is to set a high light level producing a cathode current of the order of 10^{-9}. A, which is relatively easily and reliably done and then to impose the filters of known attenuation and assume a reduced current of I_k/α applies. The assumption is that I_k is solely signal current and ignores the contribution from positive, signal-induced, ion current and ohmic leakage current.

Collection efficiency measurements on the same photomultiplier type, the Electron Tubes 9558B, have been reported as 64% [6], 86% [5] and 91% [7], all based on the above method. This range in quoted results stems partly from different experimental conditions but also underlines the difficulty in making collection efficiency measurement.

The sources of error in measure F_2 lie principally in $<G>$ because the same experiemental difficulties relating to measuring low values of I_k apply. Since $<G>$ needs to be of the order of 10^7, in order to determine $<g>$, it has to be measured by the method of gain scaling from a gain of ~ 10^4 – 10^5 at which I_k can be measured without exceeding an anode current of 100 ∝A (maximum recommended by manufacturers). Scaling by 2-3 decades always introduces uncertainties into the final result.

The multiplier gain $<g>$ refers to the amplification factor for those pulses that start as a single photo-

electron and successfully propagate to the anode. The output pulses have a spectrum of pulse heights because the secondary emission gain process is noisy. Pulse height distributions for photomultipliers which different dynode types are shown in **figure 2**. The multiplier gain can be calculated from these distributions by noting that

$$<g> - I_a /Ne \qquad \ldots(3)$$

where $N = \int h(q)\, dq$ is the total number of anode pulses per second. Alternatively if the multichannel analyzer is calibrated in coulombs/channel then $I_a = \int h(q) q\, dq$ where both integrals extend form 0 to ∞. I_a in equation **(3)** can be measured to high accuracy with a standard laboratory multimeter and so the error in $<g>$ is essentially that derived from the evaluation of $\int h(q) q\, dq$. The small pulses that are evident in the spectra of **figure 2**are signal and definitely not background as is sometimes assumed: they appear in both random and synchronous single photon sources. Pulse height measurements were extended to very small pulse heights so that the effect of their inclusion in the integral could be seen. The integral performed in reverse shows that straight line extrapolation to zero pulse height does not follow the contributions made from pulse heights less than 1/20 of a photoelectron equivalent (**figure 3**). The author is unaware of a way to determine the contribution made from pulse heights spanning 0 to 1/80 of a photoelectron (the last data point shown). This means that the mean multiplier gain cannot be determined accurately and assigning an error is subjective. **Table 1** summarises gain determinations for these two photomultipliers where the integration is stopped at 1/80 of a photoelectron – the mean gains are less than quoted by perhaps 5%.

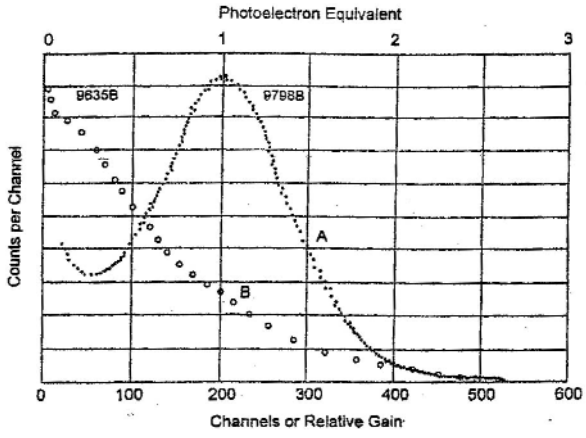

figure 2 single electron pulse height distribuitons for: (A) a linear focused multiplier with a well resolved peak; (B) a venetian blind multiplier without a peak.

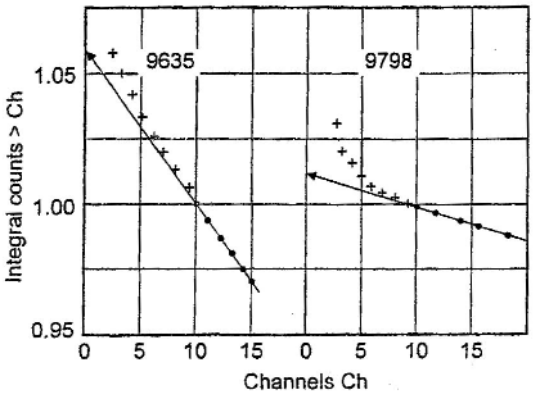

figure 3 integral pulse height distributions showing contributions from low channel numbers, +, a determined from measurements made at higher tube gain. The ordinate is normalized to the number of counts $\geqslant$10.

table 1
determination of $<g>$ by two methods and comparison with the peak of the pulse height distribution [8]. Gains are x 10^7.

tube type	I_a/Ne	$\int h(q)\, q\, dq/Ne$	$\hat{g}$
9798	2.85	2.94	3.05
9635	1.96	2.08	-

5 determination of F using light sources of known of calculable intensity

Given a single photon light source known to provide m photons per second on the photocathode and a photomultiplier with calibrated photocathode then F may be determined from $(N/\eta m)$ Light sources may be a calibrated lamp, laser, synchrotron radiation (particularly in the uv and vuv) and Cherenkov emitters. What is particularly satisfactory about this method is that F may be determined for whatever counting threshold is decided appropriate. The uncertainties associated with including all pulses in the spectrum, which detract from the methods described in Section 4, do not apply here.

Besson et al. [4] used a deuterium lamp of calibrated spectral radiance to deduce absolute quantum efficiencies in the vuv range of the spectrum. The method is based on photon counting with a series of apertures and filters attenuating the light by some six decades. No error anlaysis is presented but uncertainties in attenuating light sources in a controlled way suggests to the present author that the errors may be as large as 20%.

Several authors [9-11] have used light generated by the Cherenkov effect as a source of known intensity and spectral content. In the method used in Ref. [9] light is generated by a 17 GeV/c pion beam in air, while [10] and [11] use betas from ^{90}Sr decay in

water and CaF, respectively. The merit in using a beam of particles of fixed momentum lies in the simpicity of calculating the photon yield. By comparison for the ^{90}Sr source, the energy spectrum of the betas, the effects of path length, attenuation and total internal reflection in the coverter add to the complexity of arriving at the final result (see Ref. [10], for example). There is always the problem of an unknown portion of the radioisotope sticking to the walls of a liquid container – something for which it is very difficult to allow.

Silicon photodioes have the advantage of a broader spectral response than photomultipliers with quantum efficiencies approaching 100% in the red and IR regions of the spectrum. Linearity of response at the 0.01% level has been reported

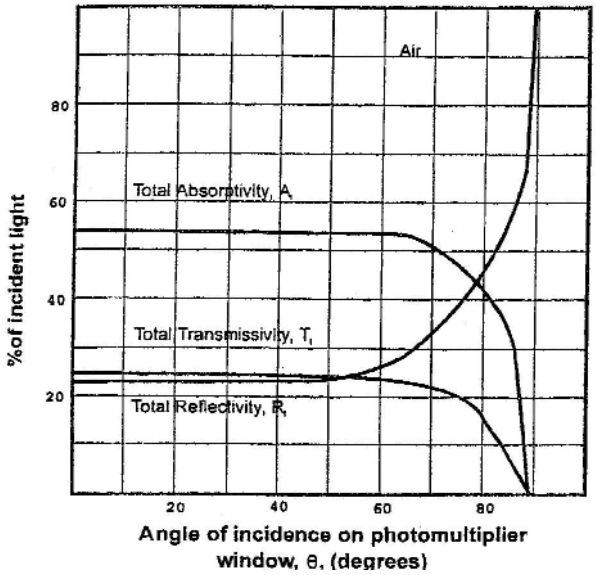

figure 4 measured optical parameters at 442 nm for an Electron Tubes 9124B illustrating why the quantum efficiency depends on angle of incidence [17]. This paper also has curves for photomultipliers immersed in water.

in Ref. [12] for at least 7 decades of operation. These characteristics lend themselves to the making of absolute measurements provided tht the light can be attenuated by a known amount and given a calibrated Si diode. Recent measurements by Oxford University and NPL based on this technique will be reported shortly [3].

The trap detector [12] is described as an ideal radiometric transfer standard with an uncertainty of only 0.02% in quantum efficiency over the visible spectrum. It consists of three Si photodidodes with their outputs connected in parallel. The photodiodes are arranged so that the incident radiation undergoes five specular reflections and is thus nearly totally absorbed. It has a limited acceptance aperature and the incident light must be essentially parallel but it undoubtedly offers opportunities for making reliable absolute measurements.

The spontaneous parametric scattering process (SPS), which produces two coincident photons, offers and interesting method for determining absolute quantum efficiences. F can be determined from measurements of single and coincident counting rates in two detectors [13-15].

6 the effect of afterpulses

All photomultipliers exhibit the phenomenon of afterpulses where a proportion of signal pulses is followed by a time correlated afterpulse. The magnitude of the afterpulse ranges from a fraction of a photoelectron up to about 10. This should be allowed for in Equation **(3)** for example by modifying the anode current as follows:

$$I_a = Ne<g>(1 + \gamma n') \qquad \ldots(4)$$

where n' is the average size of the afterpulses and γ is the afterpulse rate. Photomultipliers exhibit afterpulse rates ranging from 0.1 to 5% with the higher figure referring to photomultipliers used in HEP and astrophysics. It is not only the magnitude of the correction (up to 15%) that is worrying but also the uncertainty in calculating the correction. The methods using standard light sources described in Section 5 are also sensitive to afterpulses but the degree to which they may contribute to the absolute quantum efficiency calibration depends on the details of the experiment – for example, whether coincidence requirements with other photomultipliers are demanded.

7 conclusions

The reliability of making collection efficiency measurements by traditional methods described in Section 4 is affected by considerations such as

- linearity of the photomultiplier with gain,
- dead time correction uncertainties,
- uncertainty in counting the small anode pulses,
- systematic effects introduced by attenuating the light,
- difficulty in measuring low cathode currents,
- afterpulses.

Most of these are avoided in the methods described in Section 5 but the following may be important when using calibrated light sources

- errors in the calculation of Cherenkov light,
- uncertainties in assumed attenuation by apertures or use of inverse square law.

Effects that also need consideration are

- polarisation of the light,
- quantum efficiency is temperature sensitive [16],
- multiplier gain depends on mean anode current [16],
- collection efficiency is sensitive to magnetic fields [16].

Underlying all the experimental techniques described here is perhaps the most imporant consideration of all. To what extent do the measurement conditions: mimic those under which the photomultipliers will ultimtely be employed; relate to conditions under which the photocathode sensitivity was calibrated? **Figure 4**taken from Ref. [17] shows very nicely that where wide angle light is incident on the photocathode, the quantum efficiency data supplied with the photomutliplier will be invalid because the calibration refers to normal incidence.

In conclusion the author has the opinion that absolute calibrations of better than 10% accuracy represent a milestone in measurement technique.

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DS_ R/P091 Issue 3 (26/08/15)