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R/P095

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1 introduction

There is a golden rule for light detection instrumentation that is often forgotten, and that is: get the signal up! Although reducing the background (another term for unwanted signal) is undoubtedly worthwhile, the best return lies in finding ways in which to increase the signal. There is a theoretical basis to these statements stemming from the statistical nature of light detection. For those detectors and light sources that obey Poisson statistics, and fortunately for the purpose of this article the majority do, resolution and signal recovery formulae have the form given in equations (1) and (2) below.

If the measurement derives from the detection of m photoelectrons then the standard deviation on this number is $m^{½}$ with a signal to noise ratio of:

$$S/N = m/m^{½} = m^{½} \qquad \ldots(1)$$

The quality of performance of an instrument, often stated in terms of its resolution capability, improves according to (1) as the square root of the magnitude of the light detected - implying that one has to work disproportionately hard to achieve improved performance. It is also easily shown, by further application of Poisson statistics, that the figure of merit (FOM) relating to instruments where a wanted signal S per second has to be recovered from an accompanying background B per second that:

$$FOM = S^2 / B \qquad \ldots(2)$$

The argument in favour of increasing S is obviously stronger in (2) than in (1) because of the S^2 dependence, but the instrument designer seeking the optimum performance must aim to achieve improvements on both.

2 practical considerations

There are many ways in which to increase the light signal,for example, through optimising light collection, but in this article we want to highlight what can be gained by matching the detector spectral response curve to the emission spectrum of the light carrying the signal. Although we have taken the specific example of light emission from scintillators, the methodology applies quite generally to any light source characterised by an emission spectrum spanning some wavelength band, for example an LED or an incandescent lamp. Regarding detectors, we have been specific by referring to the three types of photocathode most commonly used in photomultipliers, but the arguments are equally valid for other types of optical detector, such as APDs.

The organic and inorganic scintillators commonly used for nuclear radiation detection have the light emission spectra shown in **figure 1**. These have been taken from manufacturer's catalogues and are assumed to be typical. Photocathode response curves for the blue-green sensitive bialkali, the green enhanced bialkali and the S20 (multialkali) from which all scintillation counting applications are met, are given in **figure 2**.

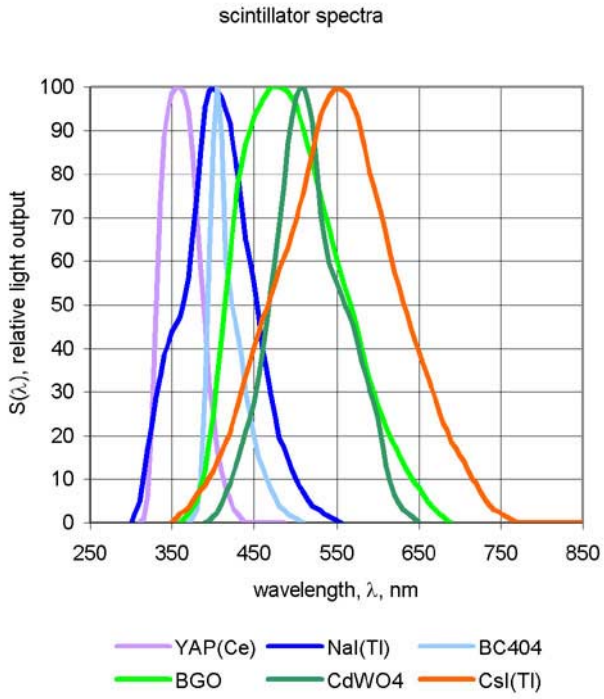

figure 1 emission spectra for some commercially available scintillators.

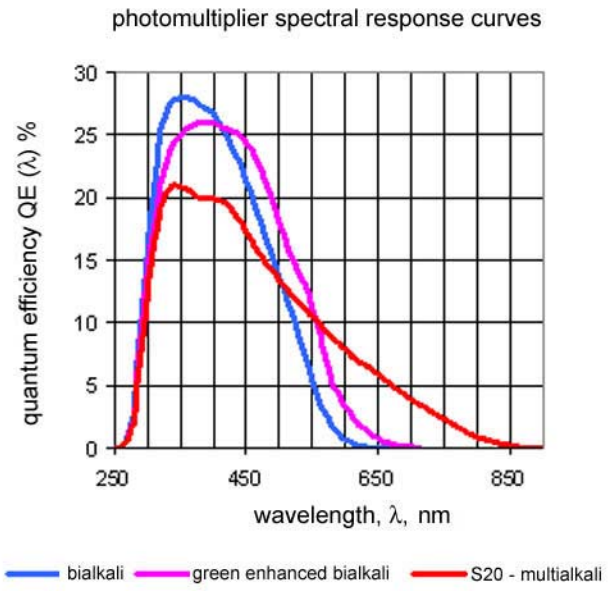

figure 2 typical quantum efficiency curves for photomultipliers best suited to scintillation counting [1].

These curves really are typical of what Electron Tubes produces and other photomultiplier manufacturers offer something similar. The question to be answered is: how do you select the most appropriate photocathode for each scintillator type and what is the expected signal level? What we seek is the average quantum efficiency, $\overline{QE}$, for each photocathode type when viewing the light from a particular scintillator because, clearly, the higher this number, the better the match. To determine $\overline{QE}$ we must weight QE(λ), the quantum efficiency at wavelength λ, with the intensity of the light at that wavelength and repeat this at all wavelengths. This is what physicists call folding one function with another and is described mathematically by

$$\int QE(\lambda).S(\lambda)d\lambda \,/\, \int S(\lambda)d\lambda$$

For computational purposes we can use the discrete form of this, given by (3), which will provide accuracy greater than the uncertainty inherent in the data that is being used.

$$\overline{QE} = \frac{QE(\lambda_1).S(\lambda_1) + QE(\lambda_2).S(\lambda_2) + QE(\lambda_3).S(\lambda_3) + \ldots + QE(\lambda_n).S(\lambda_n)}{S(\lambda_1) + S(\lambda_2) + S(\lambda_3) + \ldots + S(\lambda_n)} \quad \ldots(3)$$

Results have been computed using the data in **figures 1** and **2**, taken in 5 nm steps and covering the entire wavelength region of interest, resulting in the entries listed in **table 1**. The scintillators have been entered in the table starting on the left with YAP(Ce) with peak emission in the uv-blue region of the spectrum and ending with CsI(Tl) with emission biased more towards the red end of the spectrum. The bialkali types are the obvious choice when using YAP(Ce), NaI(Tl) and plastic scintillators because these photocathodes have the highest effective QEs for the light emitted. For those scintillators emitting in the green-red region we see that green enhanced bialkali is the best choice, even for CsI(Tl), although there are still users who specify the S20 photocathode for this purpose (a needlessly expensive option with concomitant higher dark current).

The computation of (3) reveals the narrow wavelength region from which 80% of the major contributions to QE derive. This is given in **table 2**. This information is useful for specifying a photomultiplier selected on the basis of its spectral response (or on just a spot wavelength) - it is obvious at a glance which region of the wavelength scale is most relevant. The penultimate entries in **Table 2**, giving the luminosity yield of scintillators in photons/keV of energy deposited, have been taken from [2] and [3] and confirmed by measurements made by the author. From a S/N perspective we want to know which photocathode type gives the highest photoelectron yield because this is central to the arguments embodied in equations (1) and (2). These figures, given as the final entries in the table, refer to the highest attainable yield based on the optimal choice of photocathode for each particular scintillator.

3 conclusions and cautions

A note of caution is urged in the use of the spectral emission curves assumed for the scintillators in this article. The actual luminosity depends on the batch, the dimensions, the reflectivity of the encapsulation and finally on who manufactured the sample. The same caution is urged with regard to the photomultiplier sensitivity curves assumed. In this instance these are truly median catalogue specifications. In really critical low light level or high resolution applications where every photoelectron is important, the scintillator and the photomultipliers should be ordered to an agreed higher level specification. Getting the combination right could make all the difference to achieving a successful outcome.

In this paper we have demonstrated the importance of knowing the spectral content of the source of the incident light. Given this information you can then decide which photocathode type will give the best match and hence the highest photoelectron yield. This is particularly important in those scintillators where the light output is rather low - such as the plastic range represented by BC400 and BC404 (note BC400 is a general purpose scintillator that emits more light in the green region of the spectrum than BC404 which, however, has a faster decay

time). YAP(Ce), BGO and CdWO4 also give low light output compared with NaI(Tl) and CsI(Tl). Historically manufacturers have quoted the light output of scintillators in terms of anthracene which was one of the first materials commercially available. Anthracene is little used nowadays primarily because of its low density and some crystal manufactures prefer to quote luminosity with reference to NaI(Tl) and an S11 photocathode. The problem is that the S11 photocathode is obsolete having been replaced by the green enhanced bialkali which, however, has a similar spectral response but lower dark current. So the old standard of NaI(Tl) and S11 serves as a reasonable measure of yield, but in the author's view users really need to know the luminosity in direct units of photoelectrons / keV, as has been given in **table 2**.

4 references

[1] Electron Tubes Ltd Photomultiplier Brochure, pmt/03.

[2] N Muira in Phosphor Handbook (eds S Shionoyaand W M Yen) 521-537 CRC Press, Boca Raton, FL, 1999

[3] Caesium Iodide data sheet, Thermo Hilger Analytical Ltd Westwood, Margate CT9 4JL, UK

table 1 effective quantum efficiency $\overline{QE}$(%) of the three most popular photocathode types for the scintillator materials quoted.

Photocathode		YAP(Ce)	NaI(Tl)	BC404	BC400	BGO	$CdWO_4$	CsI(Tl)
Blue-green bialkali	(B)	27	25	25	22	14	11	8
Green enhanced bialkali	(G)	25	25	25	24	18	16	11
S20 (multialkali)	(R)	20	19	19	18	14	13	11

table 2 the wavelength band (nm) that provides 80% of the photoelectron contribution. The fourth row gives the light yield in photons per keV energy deposited and the fifth row refers to the highest attainable yield. For example, the entry of 1.9 for YAP(Ce) refers to a blue-green bialkali photocathode with $\overline{QE}$ = 27%.

Photocathode	YAP(Ce)	NaI(Tl)	BC404	BC400	BGO	$CdWO_4$	CsI(Tl)
Photons/keV	7	40	8	8	8	14	60
Blue-green bialkali	330-385	350-450	390-410	415-460	410-510	450-535	425-550
Green enhanced bialkali	335-385	355-460	390-435	415-465	415-525	450-545	435-570
S20 (multialkali)	335-385	345-450	390-435	415-460	410-540	450-560	435-605
Photoelectrons/keV	1.9	10.0	2.0	1.9	1.4	2.2	6.6
Photocathode	B	B or G	B or G	G	G	G	G or R

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