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Measuring the absolute light yield of scintillators

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Abstract

The absolute light yield of four different scintillation materials measured with two photomultiplier tubes and two avalanche photodiodes is presented. Commonly, the photoelectron yields and electron–hole pair yields are corrected for the quantum efficiency of the detector, as specified by the manufacturer, to obtain the absolute photon yield. However, the effective quantum efficiency under scintillation measurement conditions is substantially higher due to back reflection. Only when back reflection is properly accounted for, the absolute photon yields obtained with the photomultipliers agree with those obtained with the photodiodes. The effect of optical coupling between the scintillator and detector is also discussed.

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Keywords: Absolute light yield; Quantum efficiency; Reflection; Optical coupling

1. Introduction

Determination of the absolute photon yield of scintillators is commonly based on the photoelectron yield measured with a photomultiplier tube (PMT) or the electron–hole pair yield measured with a photodiode [1–4]. The yields are then corrected for the quantum efficiency of the detectors as specified by the manufacturer. These quantum efficiencies are usually determined with light at normal incidence on the detector, see arrow 1 in Fig. 1a. This is not the situation under scintillation measurement conditions where angles vary. Furthermore, reflected light is back reflected by the scintillator wrapping [2], arrow 2 in Fig. 1a, and optical coupling is used. Both enhance the specified quantum efficiency (QE) of a PMT and/or photodiode. In this work, the absolute photon yields of CsI(Tl), CsI(Na), $Bi_4Ge_3O_{12}$ (BGO), and $YAlO_3$(Ce) (YAP(Ce)) scintillators are measured employing PMTs and avalanche photodiodes (APDs). Only by properly accounting for back reflection and self-absorption in crystals, photon yields determined with PMTs are consistent with those determined with APDs.

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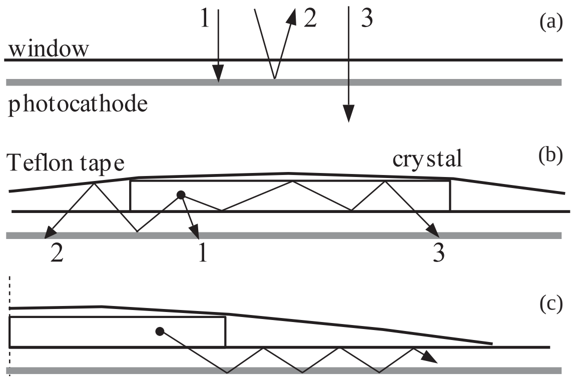

Fig. 1. (a) The incident (1),reflected (2) and transmitted light (3) at a photocathode. (b) Direct absorbed (1), back reflected (2) and trapped (3) scintillation light. (c) Multiple internal reflected light in window/photocathode substrate. (refraction is left out of consideration).

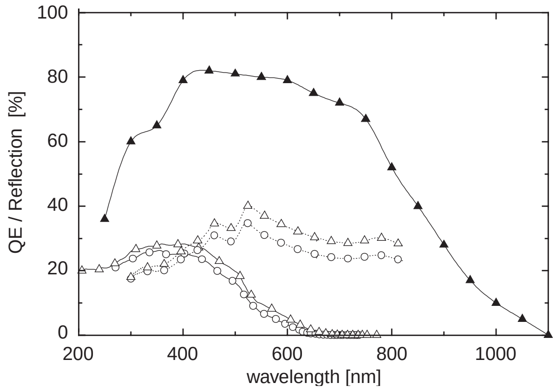

Fig. 2. Quantum efficiency (solid lines) and reflectivity (dotted lines) of the photocathode of the two PMTs: ○, PMT-I and Δ, PMT-II). ▲, the APD quantum efficiency.

2. Results and discussion

Two Hamamatsu R1791 PMTs (hereafter referred to as PMT-I and PMT-II) and two windowless Advanced Photonix (type 630-70-72-510) APDs were used [5]. On one APD, hereafter referred to as APD-I, a protecting quartz window was mounted. The scintillators wrapped in white reflecting Teflon were mounted on the detectors either with or without optical coupling.

PMT photoelectron yields Y_{pe} are determined from comparison of the 662 keV full-energy peak of ^{137}Cs with the single photoelectron response. By comparing the 662 keV scintillation peak with the peak of directly detected 17.8 keV X-rays from ^{241}Am in the APD, the electron–hole pair yield Y_{eh} is obtained. All measurements were done with a shaping time of 10 μs. By limiting the APD gain below 100 and using 17.8 keV X-rays for calibration, the APD gain for detected photons is about the same as for low-energy X-rays [6]. To avoid gain drift, the APDs were stabilized at $15 \pm 0.1\,°C$. The temperature of the PMT window is about 27 °C.

Quantum efficiency curves of the two PMTs as measured by the manufacturer and that of the APDs are shown in Fig. 2, a Labsphere RSA-HP-85UV integrating sphere with a Hewlett-Packard HP8452A spectrophotometer was used to measure the diffuse/8° reflectivity of the PMT photocathodes as shown in Fig. 2.

Results on scintillators with dimensions of $\varnothing 8 \times 1$ and $10 \times 10 \times 1\,\mathrm{mm}^3$ are shown in Table 1. Columns 2 and 3 compile the photoelectron yields Y_{pe} and columns 4 and 5 electron–hole pair yields Y_{eh} measured without using an optical coupling. The situation for PMTs is illustrated in Fig. 1b. Photons may be absorbed in the photocathode directly, see arrow 1. Photons reflected from the PMT can be back reflected by the Teflon wrapping and still be detected, see arrow 2. Photons can be multiply reflected in the crystal before detection, see arrow 3.

To obtain the absolute photon yield Y_{ph}, we use

$$Y_{ph} = Y_{pe}\frac{1 - R_{eff}}{0.98 \cdot QE_{eff}} \tag{1}$$

where QE_{eff} is the effective quantum efficiency derived from the manufacturer and R_{eff} is the PMT effective reflectivity. Both are averaged over the spectral profile of the scintillator emission spectrum. 0.98 is the reflection coefficient estimated for the 1 mm total thickness Teflon layer wrapping [7]. $1-R_{eff}$ provides a first-order correction for photons (multiply) reflected by the PMT and back reflected by the Teflon wrapping. The values for QE_{eff} and R_{eff} for both PMTs and the four types of scintillators used are compiled in Table 1, columns 13–16. The photoelectron

Table 1
The mean photoelectron yield, Y_{pe}, electron–hole pair yield, Y_{eh}, measured without optical coupling and absolute photon yield, Y_{ph}, of scintillators measured with two PMTs and two APDs. The ratio of the photoelectron yield R_{pe} and electron–hole pair yield R_{eh} measured with and without optical grease. The average emission wavelength λ_{av}, effective quantum efficiency, QE_{eff}, and refectivity, R_{eff}

Sample	Y_{pe}[1000/MeV]		Y_{eh}[1000/MeV]		Y_{ph}[1000/MeV]				R_{pe}	R_{eh}	λ_{av} (nm)	QE_{eff}		R_{eff}	
	PMT-I	PMT-II	APD-I	APD-II	PMT-I	PMT-II	APD-I	APD-II				PMT-I	PMT-II	PMT-I	PMT-II
CsI(Tl)	5.9	8.1	52.8	55.8	48.3	48.3	53.9	56.9	1.23	1.01	560	9.1	11.4	27.0	33.8
CsI(Na)	12.8	15.7	47.2	49.5	45.1	45.1	48.2	50.5	1.14	0.99	425	22.1	25.2	23.4	28.6
BGO	1.17	1.48	7.46	—	6.3	6.2	7.61	—	1.27	1.04	510	13.4	16.2	29.3	33.8
YAP(Ce)	4.85	5.62	15.6	—	15.4	16.0	15.9	—	1.32	1.15	360	25.6	27.9	20.7	22.5

collection efficiency of the PMTs, that have box-and-grid dynode structure, is assumed 100% [8,9].

For a PMT photocathode, the effective quantum efficiency is limited by light transmission through the semitransparent photocathode, arrow 3 in Fig. 1a, and the photoelectron escape probability from the photocathode. Both loss factors are absent in photodiodes below wavelength of 800 nm, and when all reflected photons are backreflected a 100% quantum efficiency is obtained [10]. Therefore, in the case of APDs $Y_{ph}=Y_{eh}/0.98$, and only a correction for the reflectivity of the Teflon wrapping is required. Results are shown in Table 1.

The use of optical coupling between scintillator and detector interface has several advantages. It prevents light trapping in the scintillator that may lead to photon losses due to self-absorption in the crystal. There is an additional advantage for PMT readout. Due to the optical coupling, photons may enter the PMT window with a larger angle of refraction than in the case of the air–glass interface [14]. This may lead to light trapping in the PMT window outside the crystal surface, see Fig. 1c. The multiple interactions with the photocathode and absence of photocathode transmission enhances the QE of the PMT [8,11–13].

To demonstrate this effect the ratio of the yields measured with and without optical grease for photoelectron yield, R_{pe}, and electron–hole pair yield, R_{eh}, are shown in Columns 10 and 11 of Table 1. For APDs this ratio should be equal to 1. However, if self-absorption in the crystal is important, as in the case of YAP:Ce, R_{eh} is greater than 1. With optical coupling photons are less multiply reflected in the crystal, which results in a higher electron–hole pair yield, whereas without optical grease there is a significant loss. R_{pe} for PMTs is larger than 1 not only for crystals where self-absorption is important but for all crystals, because the photocathode transmission losses are reduced by the optical coupling. The effect is largest for CsI(Tl) and BGO that emit at relatively long wavelengths, where the PMT transmission of the photocathode is large. One should notice that the increase in QE is not well defined and consequently, if employing a PMT, in principle absolute light yield should be measured without an optical coupling.

Care was taken in properly calculating absolute light yields, but still significant deviations exist between PMT and APD readout. The smaller photon yield obtained with APD-I as compared to APD-II is attributed to absorption losses in the glue used to mount the quartz window. Other error sources are: (1) systematic errors in the specified quantum efficiency curves, (2) smaller than 100% photoelectron collection efficiency in the PMTs, (3) temperature differences in PMT and APD readout, (4) APD gain difference between photon and low-energy X-ray detection. Because (1) and (2) do not apply to APD readout, we regard the use of APDs with almost 100% effective quantum efficiency and an optical coupling to minimize light trapping as the most reliable method to determine absolute photon yields.

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