



Spectral matching factors for LaBr₃:Ce crystals coupled to Hamamatsu H8500 family PMTs

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ABSTRACT

The matching between the spectral distribution of the scintillation light from a LaBr₃:Ce crystal and the spectral distribution of the quantum efficiency of a Photomultiplier Tube (PMT) can be characterized by a matching factor whose value depicts, in the range from 0 to 1, the efficiency of PMT for the crystal. A systematic survey of literature was carried out identifying a set of 44 LaBr₃:Ce emission spectra and 11 spectral quantum efficiencies of PMTs, all published in the years 2002–2010. Results showing the values of matching factors calculated for all the spectral combinations are presented and commented upon.

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1. Introduction

The present study was carried out to evaluate the response of a scintillation detector for high resolution radionuclide imaging according to the method used by Price [1] for particle detectors and later applied for studies of source–detector spectral matching [2–5].

In particular this work is aimed to evaluate, among the elements affecting the detector response, the spectral matching factor (SMF) values describing the matching between the spectral distributions of scintillation light and quantum efficiency (QE) for assemblies, presently in our interest [6,7], based on LaBr₃:Ce scintillation crystals (say *crystals* in the following) and PMTs of Hamamatsu H8500 family. The PMT set was extended to Hamamatsu R6231 PMT for comparison purposes because it has been used in the past years, by us as well as by other groups worldwide, for characterizing LaBr₃:Ce crystals as gamma-ray spectrometers.

A systematic survey of literature on spectral data was carried out obtaining a set of 44 crystal emission spectra $S_{(\lambda)}$ [8–35] and 11 spectral $QE_{(\lambda)}$ of the given PMTs [36–41], all published in the years 2002–2010. The term *family* indicates the Hamamatsu

models of assemblies or PMTs having size and geometrical configuration of window–photocathode comparable with those of the H8500 Flat-Panel PMT [36].

A set of $44 \times 11 = 484$ SMF values corresponding to all the combinations of crystal–PMT are presented and commented upon.

2. Methods

This section is divided into four parts dedicated, to summarize: (1) background information, (2) data processing, and specifications of (3) crystals emission spectra as well as (4) PMT spectral quantum efficiencies.

2.1. Background

According to Ref. [1], the number of photoelectrons n_e emitted by the photocathode per unit of energy of incident gamma-ray absorbed in the crystal can be written as

$$n_e = C_{gp} T_p F_p QE_{eff} \quad (1)$$

where C_{gp} is the conversion efficiency of absorbed gamma-ray energy to light photons, T_p the transparency of crystal for its own scintillation light, F_p the fraction of light photons that would reach the photocathode if $T_p = 1$, and QE_{eff} the effective QE representing

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the value averaged over the emission spectrum of crystal. In turn, QE_{eff} can be written as

$$QE_{eff} = QE_{peak} SMF \quad (2)$$

where QE_{peak} is the peak value of QE, and SMF the figure of merit expressing the degree to which spectral distributions of crystal and photocathode overlap.

The SMF value for crystal–PMT assemblies was calculated as

$$SMF = a/b \quad (3)$$

with

$$a = \int_0^\infty S_\lambda QE_\lambda d\lambda, \quad b = \int_0^\infty S_\lambda d\lambda \quad (4)$$

where both spectral distributions are normalized to unity. As one can observe, the values of the quantity SMF range from 0 to 1. More in detail, the value $SMF=0$ characterizes separated distributions, and $SMF=1$ indicates completely matching ones.

Eq. (4) can be written in discrete form, suitable for numerical calculations, as

$$a = \sum_{\lambda_i}^N S_{\lambda_i} QE_{\lambda_i}, \quad b = \sum_{\lambda_i}^N S_{\lambda_i} \quad (5)$$

SMF data were calculated from Eqs. (3) and (5), where $S_{(\lambda_i)}$ and $QE_{(\lambda_i)}$ values were calculated, in 2.5 nm steps covering the wavelength intervals of Eq. (6).

According to Ref. [4], the summation bounds of Eq.(5) can be defined as

$$\lambda_1 = \text{Max}[\lambda_{\min_{Scint}}, \lambda_{\min_{PMT}}], \quad \lambda_N = \text{Min}[\lambda_{\max_{Scint}}, \lambda_{\max_{PMT}}] \quad (6)$$

where $\lambda_{\min_{Scint}}$, $\lambda_{\min_{PMT}}$, $\lambda_{\max_{Scint}}$, and $\lambda_{\max_{PMT}}$ are the lower and upper bounds of the emission spectrum of crystal and of the PMT spectral response, respectively. Bounds are reported in Table 3.

2.2. Data processing

Spectral curves were digitized using the Engauge Digitizer free software [42], producing numerical data sets for further calculations. All digitized distributions were normalized by assigning unity to its peak values in order to make results independent of its peak values.

Afterward, in order to express the distributions in analytical form for SMF calculations at given wavelength steps, data were processed using the SciDAVis free software [43] with a non-linear fitting procedure based on the multi-Gaussian model of Eq. (7) and on scaled Levenberg–Marquardt algorithm:

$$f_{(\lambda)} = f_0 \sum_{i=1}^{N_G} A_i \left(\sqrt{2/\pi} \right) / w_i \text{Exp}(-2((\lambda - \lambda_{c_i})/w_i)^2) \quad (7)$$

where $f_{(\lambda)}$ indicates an emission spectrum $S_{(\lambda)}$ or a quantum efficiency $QE_{(\lambda)}$ distribution, f_0 offset value, A_i area of i th Gaussian curve, w_i two times the standard deviation of i th Gaussian, λ_{c_i} wavelength of i th centroid, and N_G number of Gaussian addends used for fitting.

2.3. Emission spectra

Table 1 reports the specifications of the $\text{LaBr}_3:\text{Ce}$ emission spectra obtained from literature [8–35]. Spectra are listed by increasing *Emission Spectrum Id.*, whose value corresponds to the rank of minimum SMF values calculated for the given emission spectrum and the entire set of QE distributions. Clearly, the higher the *Emission Spectrum Id.*, the better the matching.

Table 1 also reports the reference to the paper in which spectra were published, the cerium content in the crystal, the modality of luminescence excitation, and the crystal temperature at measurement time.

Emission spectra whose temperature was not specified can be, reasonably, assumed as measured with crystals at room temperature, while no hypothesis about the values of not specified cerium contents seems realistic.

2.4. Spectral quantum efficiencies

The basic features of Hamamatsu H8500 family consist of external dimensions of 52 mm × 52 mm, head-on window with 49 mm × 49 mm active area, charge multiplication based on metal channel technology, and multi-anode charge collection. The number of multiplication stages, as well as the number of anodes, can vary model by model. The PMTs of H8500 family considered in the present study differ in photocathode type, window material, and window thickness.

The Hamamatsu R6231-01 is a 51 mm overall diameter head-on PMT with a 46 mm active diameter. Its charge multiplication is based on box and linear focusing technology with 8 stages and single-anode charge collection.

Table 2 reports the spectral QE specifications obtained from Hamamatsu data-sheets [36–41]. Responses are arranged, from left to right, by increasing *Spectral QE Response Id.* whose value corresponds to the rank of minimum SMF values calculated for the given set of spectral emissions of crystals. Clearly, the higher the *Spectral QE Response Id.* (from A to K), the better the matching. Table 2 also reports the reference to the data-sheet, the window material and thickness, the photocathode material, and the kind of spectral response (almost all typical).

3. Results and discussion

Digitized emission spectra and spectral QEs were fitted to the model of Eq. (7) with number of Gaussian addends $N_G=2-4$ and $N_G=4-5$, respectively. R -squared coefficients, measuring the regression quality, were in the range from 0.9870 to 0.9999 and from 0.9983 to 0.9999, respectively.

Fig. 1 shows the calculated spectra all together for qualitative comparison. Emission spectra were plotted with gray lines referenced, when necessary, by circled numbers. QEs were reported with black lines; some curves were marked by letters enclosed in rectangles.

Hereafter crystals emission spectra are indicated by their number between italic round brackets, and numbers between italic square brackets are used for referring to PMT spectral responses.

Emission spectra nos. (1) and (2) show significant queues at the lowest and highest wavelengths [8,35], respectively. Spectral QE of R6231 [40] shows the rightmost response [A]; spectral responses [I], [J], and [K] of H8500 [38,39] with UV-glass and synthetic silica windows, respectively, show the best responses at low wavelengths.

This section is divided into four subsections dedicated to present the results regarding: (1) $\text{LaBr}_3:\text{Ce}$ emission spectra, (2) spectral matching factors, and (3) PMTs spectral QE and QE_{eff} .

3.1. $\text{LaBr}_3:\text{Ce}$ emission spectra

A rule of spectra classification was adopted based on relative height of the two main peaks. Emission spectra with higher first peak were classified as type a, the ones with second peak prevailing were classified as type b, and type c grouped the remaining spectra characterized by single peaks.

Table 3 shows type, bounds, and peak wavelength values of spectra. Data were numerically calculated by Eqs. (3) and (5) with the bounds of Eq. (6) using its analytical expressions obtained by

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