Absolute Light Output of Scintillators

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Abstract

The absolute light outputs of BGO, CsI(Tl) and some new Ce-doped crystals have been measured to an accuracy of about ±5 % using calibrated XP2020Q photomultipliers and standard S3590-03 and S2740-03 photodiodes. The use of small crystals, 9 mm in diameter and 1 mm thick, reduces the corrections for imperfections in the light collection process and in the photoelectron collection by the photomultipliers. The measured light output of 8500±350 ph/MeV (photons/MeV) for the BGO crystals agrees well with the earlier measurement done by Holl et al. The carried out study highlighted the importance of the spread in the published emission spectra of the crystals which seems to limit measurement accuracy. Finally, a simple comparative method of measuring light output to an accuracy of ±10 %, is proposed using an uncalibrated XP2020 photomultiplier and a 1 mm thick BGO crystal as a standard.

I. INTRODUCTION

The measurement of the absolute light output of a scintillator is very complex and difficult. Photons created by nuclear radiation in the scintillator are affected by many processes that reduce their number before they are converted into photoelectrons in photomultipliers (PMTs) or electron-hole pairs in Si photodiodes. One has to consider: the size of the scintillator crystal and its self-absorption, the quality of the reflector material, the type of photosensor and the matching of the scintillator emission spectrum with the photosensor sensitivity spectrum, the quantum efficiency of the photosensor and the reflectivity of its entrance window, and finally the photoelectron or electron-hole pair collection efficiency.

Some papers in the literature present accurate methods of measuring light output [1-5]. Even so, there is a large spread in the measured light yield of the most popular crystals, e.g. NaI(Tl), BGO and CsI(Tl). The spread may be associated with differences in the quality of the crystals from different suppliers. Various assumptions, however, used in calculating the correction factors, notably that for the light collection efficiency may also affect the published data.

In other investigations, the light output of a scintillator is very often determined by a simple comparison with that of a BGO or NaI(Tl) reference without sufficient consideration of the quality of the reference crystal or the measuring conditions This approach introduces misleading data in the literature.

Sometimes, the light output of a scintillator is expressed as the number of photoelectrons or electron-hole pairs for a specified type and sensitivity of photosensor [6-11]. Such measurements of light output are generally accurate since they are determined using simple and reproducible method. While the number of photoelectrons/electron-hole pairs is very important, and often sufficient for the user of scintillation counters, however, it is not enough for scintillator development and research.

The aim of this work was to study the light output of different scintillators using two calibrated XP2020Q photomultipliers and two standard S3590-03 and S2744-03 photodiodes. The measured quantities, numbers of photoelectrons and electron-hole pairs, were converted into numbers of photons using the quantum efficiency of the photomultiplier or photodiode, respectively. Measurements were made for several samples of BGO (further considered as the reference crystal), CsI(Tl) and some new Ce-doped scintillators. Based on the study done by Holl et al [2] BGO seems to be the best material for a standard scintillator and this undoped crystal has the lowest spread of light output between samples from different suppliers. Since the determination of the light collection efficiency is difficult, small BGO samples, 9 mm in diameter and 1 mm thick, are proposed as a standard. For such a scintillator, the efficiency of the collected light approaches 100%. The small diameter of the samples is well-suited to a standard 52 mm XP2020Q PMT whose advanced focussing system ensures that all photoelectron produced (in the central region of the photocathode) are collected.

The calculated number of photons detected by both photosensors are compared and discussed relative to earlier results. Finally, the possibilities of a simple method of light output measurement based on the comparison with the output of BGO and its expected accuracy are discussed.

II. OUTLINE OF THE PROBLEM

The measured quantity, that is, the total number of photoelectrons, (or, for Si photodiode, number of electron-hole pairs), $N_{phe}(E)$, collected at the anode due to the full-energy γ-ray events is proportional to the absolute number of photons as follows:

$$N_{phe}(E) \propto N_{ph}(E) \times \eta_L \times Q.E.(\lambda) \times \varepsilon \quad (1)$$

where:

$N_{ph}(E)$ - number of photons per energy unit produced in the scintillator at a given energy,
η_L - light collection efficiency,
$Q.E.(\lambda)$ - quantum efficiency,
ε - efficiency of photoelectron or electron-hole pairs collection.

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The number of photons per energy unit created by γ-rays in the scintillator depends on the γ-ray energy, and is lower, in general, in a low energy region below 100 keV and reaches a maximum at 100 - 200 keV. This non-linear effect known for NaI(Tl) crystal for a long time [12] was recently studied and discussed for a number of scintillators in Ref. [13]. Thus, one has to define the energy of the γ-rays used in the measurements.

The light collection efficiency is a function of the crystal size and its shape, surface finish and refractive index. It is affected by the self-absorption of the light in the crystal and by the reflector material used. For small crystals, the error introduced by the uncertainty of the light collection efficiency is smaller than for big crystals. The estimation of this parameter seems to be crucial for the reproducible measurement of the light output.

The quantum efficiency versus wavelength has to be measured for the particular PMT or photodiode used. This quantity in the measurements of the light output of the scintillator has to be further corrected for the reflectivity of the photocathode. In the calibration procedure a part of the light which is reflected from the photocathode is lost. In the measurement with the crystal having full optical contact due to grease this part of the light can be easily collected back into the photocathode and it increases the effective quantum efficiency. This effect is particularly important for Si photodiodes because of the large reflectivity of silicon (up to about 30%). For PMTs this quantity is characterized by the reflectivity of the glass window - about 8% (4% on each side), see Ref. [14].

When considering the quantum efficiency of the photosensor for a given scintillator one has to take into account the shape of its emission spectrum. This is particularly important for PMTs for which the integral quantum efficiency has to be calculated by taking account of the emission spectrum of the scintillator upon the PMT quantum efficiency characteristic. The accuracy of the emission spectrum directly affects the measured light output.

The next factor which can limit the measured number of photoelectrons is the efficiency of photoelectron collection. For a photodiode, a collection efficiency of 100% is generally assumed [2,3]. The situation is more difficult in the case of a PMT. This quantity is never quoted by the manufacturers. For a well-designed PMT, one can assume that at least in the central part of the photocathode the collection efficiency approaches 100%. To overcome this problem, photomultipliers are often operated in photodiode mode, following Houdayar et al [15], see Refs [1,4].

Finally, the temperature of a crystal also affects its light output [3]. Furthermore, this temperature dependence is different for different crystals [16]. Clearly thus, precautions have to be taken when measuring light output.

III. EXPERIMENTAL PROCEDURES

A. Scintillators

In the first part of the study, the best known scintillators, CsI(Tl) and BGO, were tested. Several small cylindrical 9 mm diameter crystals 1 mm, 4 mm and 9 mm thick were prepared by Bicron. These were used to determine the influence of crystal thickness on the measured light output. All the BGO crystals were made from the same crystal ingot, 2 samples 1 mm thick were cut from each end, then 2 samples 4 mm thick were cut in the same way, and the middle part was used to make the 9 mm thick sample. The crystal surfaces were ground to reduce the contribution of the light trapped due to total internal reflection. This is particularly important for BGO because of its high refractive index. The crystals were coated with several layers of white Teflon tape and optically coupled to the PMT or photodiode using DC 200 silicone grease whose viscosity is 100,000 cst.

Table 1
Tested scintillators

Crystal	Ce conc. [mol%]	Size [mm]a)	Manu- facturer	Surface finish	Refr. index
BGO	-	⌀9×1 (4)	Bicron	ground	2.15
		⌀9×4 (2)	Bicron	ground	
		⌀9x9	Bicron	ground	
		1 cm^3	Scionix	ground	
CsI(Tl)	-	⌀9x1 (2)	Bicron	ground	1.78
		⌀9x4	Bicron	ground	
		⌀9x9 (2)	Bicron	ground	
GSO		10x10x5	Russia	ground	1.85
LSO	0.22%	4x5x14.5	Russia	polished	1.82
YAG	1.08	10x10x2	Preciosa	polished	1.82
YAP	0.56	10x10x5	Preciosa	ground	1.95
LuAP	0.105	5x6x1	Airtron Litton	polished	1.97

a) The numbers in brackets indicate the number of samples, no brackets 1 sample.

In the other part of the study, several new inorganic crystals, LSO, GSO, LuAP, YAP and YAG, were measured. Note, there is some spread in the size, shape and surface finish of these crystals as they were obtained at different times. An overview of all the crystals used is given in Table 1.

B. Photomultipliers and Photodiodes

Two Philips XP2020Q photomultipliers were used in the measurements. The quantum efficiency characteristics, see Fig. 1, were calibrated by the manufacturer and are relatively flat between 300 and 450 nm, then monotonically decrease with increasing wavelength. Both PMTs were operated with a type C voltage chain as recommended by the manufacturer [17]. Owing to the very advanced focussing system of this 52 mm diameter fast PMT, it was assumed that the photoelectron collection efficiency in the centre of the photocathode within a 9 mm diameter area is virtually 100 %.

In the measurements with photodiodes, two Hamamatsu diodes: a S3590-03 with 1 x 1 cm^2 sensitive area and a S2744-03 with 1 x 2 cm^2 area were used. Since we did not have any calibrated photodiodes, the typical radiant sensitivity characteristic published by Hamamatsu [18] was applied, recalculated for the quantum efficiency, following Ref. [3], see Fig. 2. An estimate of the accuracy of the typical radiant sensitivity characteristic was made by comparing the numbers of electron-hole pairs measured using two photodiodes delivered independently by Hamamatsu, and three years apart.

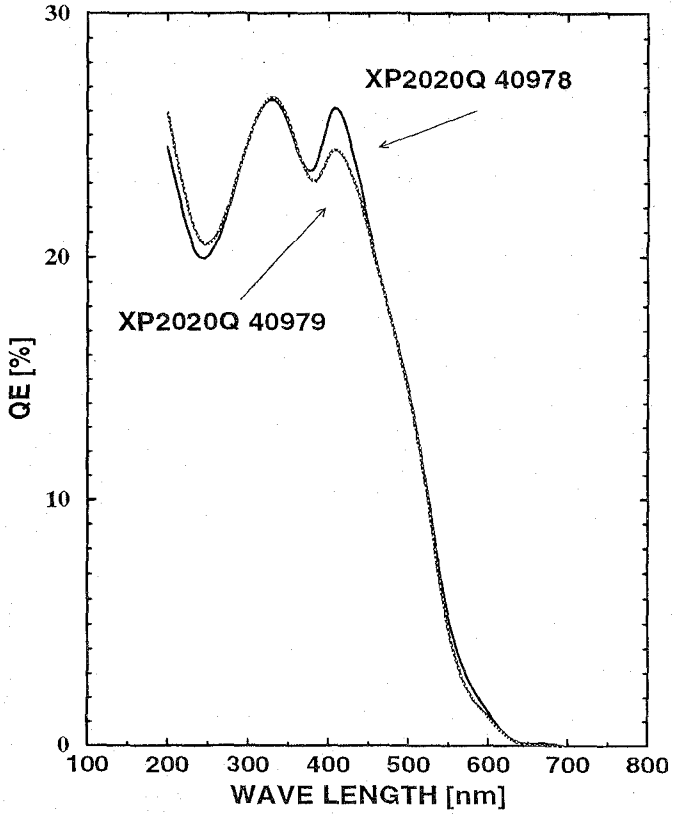

Fig. 1. Quantum efficiency of two calibrated XP2020Q PMTs.

The quantum efficiency of photodiodes is strongly affected by the wavelength-dependent reflectivity of silicon. The fraction of photons reflected varies from 34.2% at 400 nm to 19.6% at 700 nm [3]. Light reflected back into a scintillator is returned to the photodiode by a Teflon reflector around the scintillator, increasing the integral quantum efficiency as measured by Holl et al in Ref. [2]. Thus, the quantum efficiency characteristic of the photodiodes shown in Fig. 2 was further corrected in terms of the reflectivity, following Holl et al [2]. The upper curve in Fig. 2 shows the corrected quantum efficiency used in calculations of the light output of the scintillators. The fact that measurements made with two photodiodes of different shape and size, and using the common radiant sensitivity characteristic published by Hamamatsu, gave comparable results seems to justify the method of data analysis used, see Sect. IV.*B*.

In all measurements the photodiodes were operated with a bias voltage of 50 V, thus, all charge was collected, see Refs. [2,3].

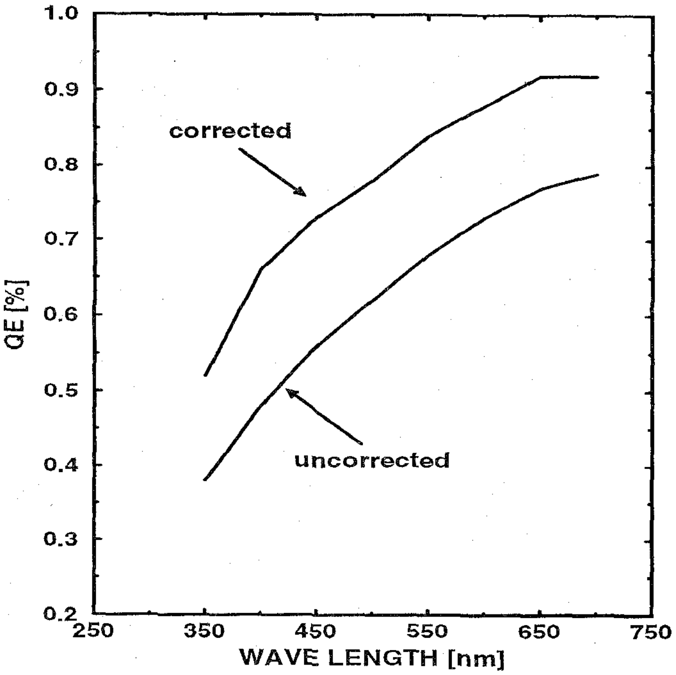

Fig. 2. The typical quantum efficiency characteristic of Hamamatsu S3590-03 and S2740-03 photodiodes. The same curve corrected in terms of the reflectivity of the photodiode, following Holl et al [2].

C. Electronics Arrangement.

All measurements were made using classic spectrometry equipment. In the measurements with the PMT, the signal collected across 1 MΩ load resistor was passed to an Ortec 113 scintillation preamplifier and then to a Tennelec TC244 spectroscopy amplifier set for 3 μs shaping time constant. The energy spectra were recorded by TUKAN PC-based multichannel analyser. The coarse gain control was used to switch between the single photoelectron spectrum and the scintillation spectrum. The gain scale on the amplifier was recalibrated using a precision pulse generator BNC Mod. PB4. The linearity of the spectrometric system and the possible offset were also checked by this generator.

The output pulse of the photodiode was sent to a charge-sensitive preamplifier and then to the same Tennelec TC244 amplifier set for 3 μs shaping time constant. The noise contributions of the S3590-03 and S2740-03 photodiodes were estimated to be 3.2 keV and 4.2 keV respectively, based on the measurements of the energy resolution of 59.6 keV γ-rays from ^{241}Am source.

IV. MEASUREMENTS AND RESULTS

All measurements made with the photomultipliers and the photodiodes were for the 661.6 keV γ-rays from a ^{137}Cs source. To increase the accuracy of the measured number of photoelectrons or electron-hole pairs all measurements were made three times and the mean value used for the analysis. The values take into account the Teflon tape coating, and coupling to the PMT or photodiode. The position of the full-energy peak corrected for background noise was determined by a computer program. A typical counting rate in the measurements with scintillators was a constant 5000 c/s to avoid any counting rate distortion and ensure that the PMT gain was stable. The temperature of the crystals was kept constant at 22±1 °C.

A. Measurements with the XP2020Q Photomultipliers

The number of photoelectrons per energy unit was measured by the Bertolaccini et al method [19], used further in Refs [6-11]. In this method the number of photoelectrons is measured directly by comparing the position of the 661.6 keV full-energy peak of γ-rays from a ^{137}Cs source with that of the single photoelectron peak, which determines the gain of the PMT. Measurements were made for all the crystals with two XP2020Q PMTs. For the crystals with no afterglow (BGO, GSO, YAP, YAG, LuAP), the measurements of the single photoelectron spectrum were made with the scintillator coupled to the PMT, without switching off the high voltage. For the CsI(Tl) and LSO crystals, a strong afterglow prevented this possibility and it was necessary to measure the single photoelectron spectrum without the crystal. Thus it was done before and after measuring the spectrum with the crystal. To avoid instability of the PMTs all the measurements were made about one hour after switching on the high voltage.

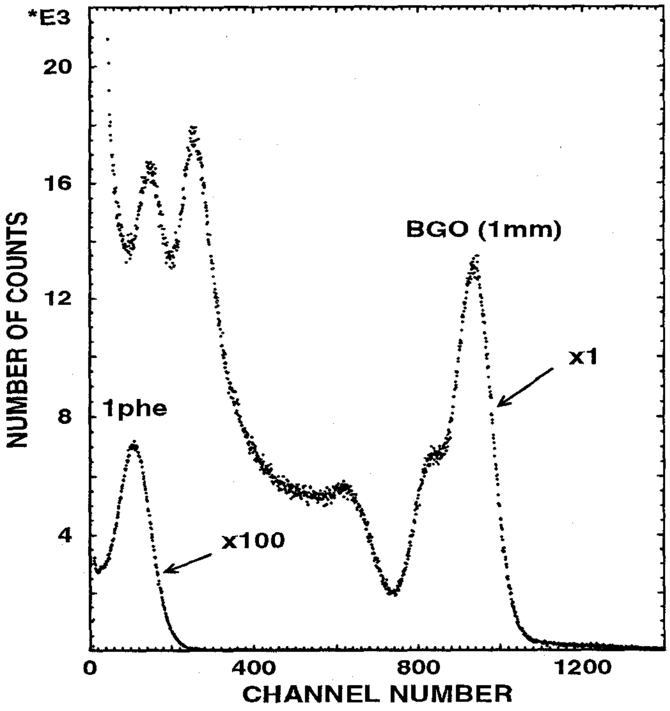

Fig.3. Energy spectrum of γ-rays from a ^{137}Cs source measured with a 1 mm thick BGO crystal compared to the single photoelectron spectrum.

Fig. 3 shows a typical energy spectrum measured with a 1 mm thick BGO crystal compared to a single photoelectron spectrum.

In Table 2, the data from all the measurements are collected for both PMTs. The numbers of photoelectrons measured by each are comparable. According to the calibration curves, see Fig.1, the quantum efficiency of each PMT is almost the same, confirming the accuracy of the calibration.

The quoted errors of ±2 % in the measurements include the statistical error in determining the centroid of both the single photoelectron peak and the 661.6 keV full energy peak from each scintillator and the reproducibility error. A larger error of ±3% is quoted for the CsI(Tl) and LSO crystals since the position of the single photoelectron peak was measured separately. Errors in the ADC and the PMTs linearity, and the amplifier gain calibration are negligible (a fraction of percent).

Table 2
Number of photoelectrons for different scintillators

Crystal	Size [mm]	Number of photoelectrons [phe/MeV]	
		PMT no. 40978	PMT no. 40979
BGO	⌀9 x 1	1150±23	1140±23
	⌀9 x 1	1220±24	1180±24
	⌀9 x 1	1170±23	1130±23
	⌀9 x 1	1200±24	1200±24
	⌀9 x 4	970±19	970±19
	⌀9 x 4	1020±20	990±20
	⌀9 x 9	920±18	910±18
	1 cm^3	930±19	870±17
CsI(Tl)	⌀9 x 1	4400±130	4160±125
	⌀9 x 1	4200±130	4120±124
	⌀9 x 4	4230±130	3980±120
	⌀9 x 9	3910±120	3900±120
	⌀9 x 9	3900±120	3850±116
GSO	10 x 10 x 5	1800±36	1800±36
LSO	4 x 5 x 14.5	5490±170	5560±170
YAG	10 x 10 x 2	1310±26	1240±25
YAP	10 x 10 x 5	4270±85	4230±85
LuAP	5 x 6 x 1	2830±57	2660±53

B. Measurements with the Photodiodes

The number of electron-hole pairs per energy unit was measured directly by comparing the 661.6 keV full-energy peak position from a ^{137}Cs source, or 1275 keV peak from a ^{22}Na source, detected in the scintillator with that of the 59.6 keV γ-rays from a ^{241}Am source detected directly by the photodiode [2,10,11]. Since the energy required to produce an e-h pair in a Si diode is equal to 3.6 eV, the number of e-h pairs for the scintillating light can be easily found. Fig. 4 shows the energy spectrum of γ-rays from a ^{241}Am source detected by a S3590-03 photodiode and from a ^{137}Cs source measured with a 1 mm thick CsI(Tl) crystal. The same gain settings were used in both measurements.

Table 3
Number of electron-hole pairs for different scintillators

Crystal	Size [mm]	Number of e-h pairs [e-h/MeV]	
		S3590-03	S2744-03
BGO	⌀9 x 1	5980±180	6360±254
	⌀9 x 1	6360±190	6340±254
	⌀9 x 1	6190±180	6340±254
	⌀9 x 1	6110±180	6370±255
	⌀9 x 4	5220±160	5460±220
	⌀9 x 4	5120±160	5680±230
	⌀9 x 9	4750±140	5080±200
	1 cm^3	4870±150	4530±140
CsI(Tl)	⌀9 x 1	41000±820	40800±820
	⌀9 x 1	39600±800	39700±800
	⌀9 x 4	38800±800	39100±800
	⌀9 x 9	35900±720	36200±720
	⌀9 x 9	36800±740	36900±740
GSO	10 x 10 x 5	4770±140	4870±195
LSO	4 x 5 x 14.5	too large	18300±360
YAG	10 x 10 x 2	14400±450	15500±480

The good agreement in the measured numbers of e-h pairs for both diodes seems to confirm that the typical radiant sensitivity curve given by Hamamatsu corresponds closely to the actual sensitivity of the photodiodes used in the experiments. The YAP and LuAP crystals are omitted from the Table 3 since the energy spectra recorded by the photodiodes did not show full-energy peaks because of the low quantum efficiency at 365 nm.

The accuracy of the measurements (about ±2%) is mainly limited by the error in determining of the peak centroids, somewhat larger (about ±3%) for the BGO crystals and GSO crystal due to their wide and worse defined full energy peaks. The not-included reproducibility error is rather small (about 1.5%).

V. LIGHT OUTPUT EVALUATION

A. Quantum Efficiency

When calculating the light output of the scintillators (ph/MeV), the integral quantum efficiency corresponding to the emission spectrum of each type of scintillator is required.

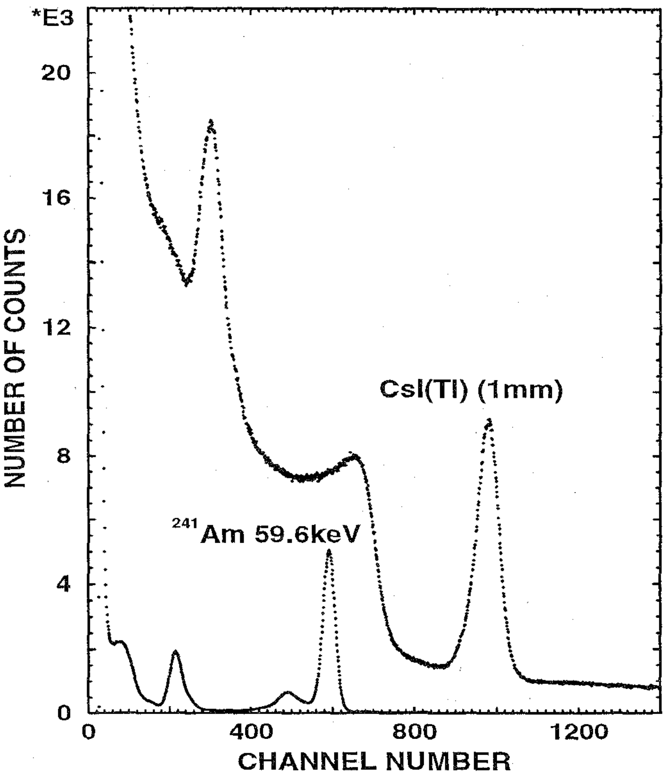

Fig. 4. Energy spectrum of γ-rays from a ^{137}Cs source measured with a 1 mm thick CsI(Tl) crystal in comparison to the spectrum of 59.6 keV γ-rays from a ^{241}Am source detected by the S3590-03 photodiode itself.

Table 4
Integral quantum efficiency for the XP2020Q PMTs

Crystal	PMT no. 40978		PMT no. 40979	
	Q.E.	Mean Q.E.	Q.E.	Mean Q.E.
BGO	0.148[a)] 0.134[b)] 0.158[c)]	0.150 ±0.007	0.143[a)] 0.130[b)] 0.153[c)]	0.140 ±0.007
CsI(Tl)	0.0723[d)] 0.0999[b)] 0.0752[c)]	0.0830 ±0.0008	0.0701[d)] 0.0968[b)] 0.0720[c)]	0.0800 ±0.0008
GSO	0.216[e)] 0.220[f)]	0.22	0.206[e)] 0.211[f)]	0.21
LSO	0.209[g)]	0.21	0.198[g)]	0.20
YAG	0.0875[h)]	0.088	0.0850[h)]	0.085
YAP	0.250[h)]	0.25	0.243[h)]	0.24
LuAP	0.250[h)]	0.25	0.243[h)]	0.24

[a)] Ref. [20], [b)] Ref. [16], [c)] Ref. [21], [d)] Ref. [22], [e)] Ref. [23], [f)] Ref. [24], [g)] Ref. [25], [h)] Ref. [26]

Table 4 lists the calculated integral quantum efficiencies of each PMT for each of the tested crystals. The values were determined using the emission spectra found in different references combined with the quantum efficiency curves shown in Fig. 1. Owing to large variations in the integral quantum efficiencies calculated using different references, the mean values were adopted in the subsequent calculations of light output.

Table 5 shows the same set of data for the photodiodes. The variations in the integral quantum efficiency are less owing to a flatter quantum efficiency curve for photodiodes.

Table 5
Integral quantum efficiency for the photodiodes

	BGO	CsI(Tl)	GSO	LSO	YAG
Q.E.	0.776[a] 0.767[b] 0.786[c]	0.836[d] 0.811[b] 0.811[c]	0.715[e] 0.732[f]	0.719[g]	0.829[h]
Mean Q.E.	0.780 ±0.005	0.820 ±0.007	0.72	0.72	0.83

[a] Ref. [20], [b] Ref. [16], [c] Ref. [21], [d] Ref. [22], [e] Ref. [23], [f] Ref. [24], [h] Ref. [25], [h] Ref. [26].

It is worthy emphasizing that the accuracy of the emission spectra used in the analysis is extremely important. In particular, it affects the agreement of the numbers of photons found using PMTs and photodiodes since their individual quantum efficiency characteristics differ a lot. The response of the PMT is more sensitive to the shorter wavelengths of the emission spectrum, while the photodiode response is more sensitive to the longer wavelengths.

B. Light Collection Efficiency

A calculation of the light collection efficiency by Monte Carlo method is simple and can be accurate if the reflectivity of the reflector and the quality of the crystal surface is known precisely, which is not a common case. Thus, in fact, the accuracy of its estimation is limited. Below, the correction for the light loss was estimated experimentally by analysing the measured light output versus thickness of the tested BGO and CsI(Tl) crystals.

C. Light Output

1) BGO and CsI(Tl)

Table 6 lists the calculated light output of all the BGO crystals measured with the XP2020Q PMTs and the photodiodes. The integral quantum efficiencies given in Tables 4 and 5 were used, respectively. Note the good agreement in the light output measured by both types of photosensors, confirming that the chosen way of analysing the data is correct.

The error of about ±5.4% estimated for the measurements made with the PMTs comes from adding in quadrature the error in the photoelectron number (±2%) and the quantum efficiency error (±5%). Note the error in light collection is not considered in this part of the evaluation, but in sect. V.*D*.

The first error was discussed in sect. V.*A*. The quantum efficiency error of ±5 % was estimated by analysing the spread of the integral efficiency given in Table 4.

Table 6
Light output of BGO crystals

BGO sample	Size [mm]	Light output [ph/MeV]				
		XP2020Q PMT		Photodiode		Mean
		No. 40978	No. 40979	S3590-03	S2744-03	
1	⌀9x1	7670 ±410	8140 ±440	7670 ±440	8150 ±470	8060 ±120
2	⌀9x1	8100 ±450	8430 ±460	8150 ±470	8130 ±470	
3	⌀9x1	7800 ±430	8070 ±440	7940 ±460	8130 ±470	
4	⌀9x1	8000 ±440	8570 ±460	7830 ±450	8170 ±480	
5	⌀9x4	6470 ±360	6930 ±370	6690 ±390	7000 ±410	6850 ±140
6	⌀9x4	6800 ±380	7070 ±380	6560 ±380	7280 ±420	
7	⌀9x9	6130 ±340	6500 ±350	6090 ±360	6510 ±380	6300 ±180
8	1 cm^3	6200 ±340	6210 ±330	6240 ±364	5800 ±340	6100 ±220

The error of about ±5.8 % quoted for the measurements with the photodiodes is somewhat larger because of the lower accuracy (±3 %) for the electron-hole number measured for the BGO crystals, see Table 3. The same quantum efficiency error (±5 %) is used. The spread of the integral quantum efficiency is lower for the photodiodes and the error is mainly because the typical radiant sensitivity curve given by Hamamatsu is used. A good agreement of the results obtained with both the photodiodes and also a good agreement with those measured with the PMTs seems to confirm the light output estimation. The last column of Table 6 shows the mean light output of all the samples of the same size seen by the PMTs and photodiodes. The errors correspond to the mean error of all the measurements with the tested samples using both types of photosensors.

Table 7 shows the measured light output of the CsI(Tl) crystals. Since the numbers of photoelectrons and e-h pairs were measured with a 3 μs shaping time constant, the values were multiplied by a factor of 1.20, corresponding to 8 μs shaping which closely approximates full light integration.

The error of about ±10 % in the measurements made with the PMTs reflects mainly the large spread in the integral quantum efficiency calculated for the CsI(Tl) crystal, see Table 4, based on different references. The peak of the emission spectrum of CsI(Tl) at 550 nm is at the edge of the quantum efficiency characteristic of the XP2020Q PMT, see Fig. 1, where the accuracy of the emission spectrum is the most critical. The same error (±5 %) on the measurements made with the photodiodes is, in turn, mainly due to the typical characteristic of the quantum efficiency. The error coming from the spread in the integral efficiency is small because of a relatively flat quantum efficiency characteristic, see Fig. 2. The total error of ±5.4 % also includes the error in the number of electron-hole pairs, see Table 3. In the last column of Table 7 the mean weighted photon numbers seen by the PMTs and photodiodes with the errors corresponding to the weighted values are listed.

Table 7
Light output of CsI(Tl) crystals

CsI(Tl) sample	Size [mm]	Light output [ph/MeV]				
		XP2020Q PMT		Photodiode		Mean
		No. 40978	No. 40979	S3590-03	S2744-03	
1	⌀9x1	63600 ±6400	62400 ±6200	60000 ±3200	59700 ±3200	59800 ±1400
2	⌀9x1	60700 ±6100	61800 ±6200	58600 ±3200	58100 ±3100	
3	⌀9x4	61200 ±6100	59700 ±6000	56800 ±3100	57200 ±3100	57700 ±2000
4	⌀9x9	56500 ±5700	58500 ±5900	52500 ±2800	53000 ±2900	56800 ±1300
5	⌀9x9	56400 ±5600	57800 ±5800	53900 ±2900	54000 ±2900	

2) Ce-Doped Crystals

Table 8 shows the results of the light output measurements for various Ce-doped crystals. The errors quoted are the same as discussed in sect. *V.1.* for BGO crystals.

Table 8
Light output of Ce-doped scintillators

Crystal	Size [mm]	Light output [ph/MeV]				
		XP2020Q PMT		Photodiode		Mean
		No. 40978	No. 40979	S3590-03	S2744-03	
GSO	10x10 x5	8200 ±440	8570 ±460	6630 ±380	6760 ±400	7540 ±210
LSO	4x5 x14.5	26100 ±1700	27800 ±1600	-	25400 ±1500	26400 ±900
YAG	10x10 x2	14900 ±800	14600 ±800	17300 ±900	18700 ±1000	16400 ±440
YAP	10x10 x5	17100 ±920	17600 ±950	-	-	17400 ±670
LuAP	5x6x1	11300 ±600	11080 ±600	-	-	11200 ±430

Note a less precise agreement of the photon numbers measured with the PMTs and photodiodes for the GSO and YAG crystals. This may reflect a less well-defined emission spectra. There is, however, good agreement for the LSO scintillator. The last column lists the mean light output of the crystals measured with the PMTs and photodiodes.

D. Absolute Light Output

The numbers of photons listed in Tables 6-8 correspond to those seen by the PMT or photodiode. To obtain the absolute light output, a correction for the efficiency of light collection has to be made. To estimate the effect the measured light output of BGO and CsI(Tl) crystals versus sample thickness is plotted in Figs. 5 and 6 respectively.

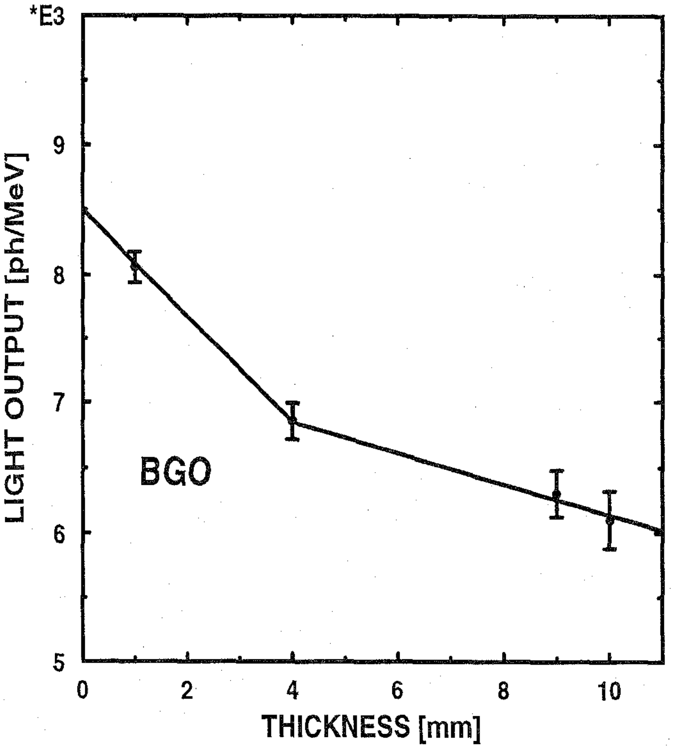

Fig.5. Light output of BGO versus crystal thickness.

Fig. 5 shows the light output of the BGO crystals seen by the PMTs and photodiodes as a function of crystal thickness. The curve extrapolated to the zero crystal thickness seems to represent the absolute light output of the tested BGO of 8500±350 ph/MeV. The experimental points correspond to the mean values of the number of photons measured for all the samples with the PMTs and photodiodes.

Fig. 6 shows the light output of CsI(Tl) crystals tested as a function of crystal thickness. Again the points represent the mean values of all the measurements. The extrapolated curve shows that for CsI(Tl), the light output at zero thickness is only about 1% larger than that of the 1 mm thick sample. This confirms for this crystal the preliminary assumption in the experiment that, for 1 mm thick samples, no significant correction is needed for the light collection process. This is significantly different from the BGO crystal, see Fig. 5, and appears to be due to the lower refractive index of CsI(Tl).

All the data on the absolute light output of the crystals studied are collected in Table 9. For the Ce-doped crystals, corrections in the light collection for different crystal thickness were made using curve for CsI(Tl), see Fig. 6. For BGO, it is assumed that an exceptionally high refractive index was responsible for the larger light attenuation.

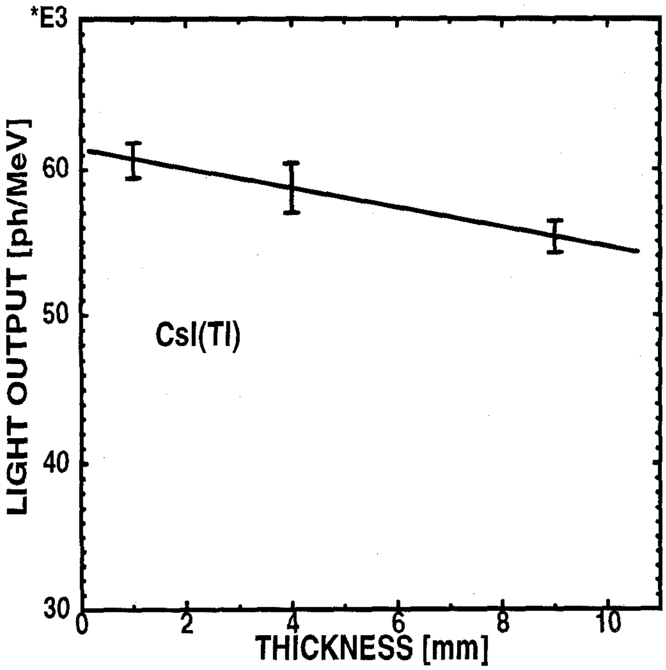

Fig. 6. Light output of CsI(Tl) versus crystal thickness.

Table 9
Absolute light output of tested scintillators

Absolute light output [ph/MeV]						
BGO	CsI(Tl)	GSO	LSO	YAG	YAP	LuAP
8500 ±350	61000 ±3000	7620 ±380	27300 ±1400	16700 ±660	18000 ±900	11300 ±450

For the 1 mm thick crystals (BGO, YAG and LuAP) the total error of ±4% was adopted. For thicker crystals (GSO, LSO, YAP) the total error of ±5% was estimated because of a larger correction for the light collection efficiency. The error for the CsI(Tl) crystal is also larger because of a lower accuracy of the number of photons measured mainly with the photomultipliers, see Table 7.

The absolute light output of BGO of 8500±350 ph/MeV agrees well with that of 8200±350±400 ph/MeV reported by Holl et al [2] measured with samples of comparable size and with that of 9000 ph/MeV given by Dorenbos et al in Ref. [13].

The absolute number of photons for CsI(Tl) of 61000±3000 ph/MeV also agrees well with that of 64800±3200 ph/MeV reported in Ref. [3] and is about 20 % larger than 51800±2150±2600 ph/MeV given by Holl et al in Ref. [2].

It is more difficult to make a comparison of measured photon numbers with those reported in earlier papers for the new Ce-doped crystals. The quality and composition of samples of the new crystals may vary between manufacturers as the crystals are still in the development stage. This is illustrated in particular by the light output measured for the LuAP crystal [26,27]. Thus, it is important to note the good agreement of the light output of 27300±1400 ph/MeV measured for the LSO crystal with that of 25000±2500 ph/MeV reported by Dorenbos et al in Ref. [28]. Our LSO crystal [11] was grown in Russia while in Ref. [28] the crystal grown by Melcher and Schweitzer [25] was studied. It is also worth highlighting that the same experimental method was used in Ref.[28] based on the measurement of the photoelectron number with an XP2020Q PMT.

Nevertheless, even this limited comparison with the results of earlier works shows that the method used to determine the light output is sound. Note that it is based fully on the optimization of the experimental conditions and the experimental determination of the correction factors. Finally, the absolute light output of the different crystals listed in Table 9 reflect the present status of scintillator development.

VI. COMPARATIVE METHOD OF LIGHT OUTPUT MEASUREMENTS

Based on the above results of the light output of scintillators, a simple comparative method is proposed using a good reference BGO crystal and a typical, but uncalibrated PMT. The principle of the method is well known and is based on a simple comparison of the position of the full-energy peak of 662 keV from a ^{137}Cs source detected with the use of the tested crystal to that measured with the reference crystal. Results of such comparison for all the tested crystals are gathered in Table 10. The measurements were made with an uncalibrated XP2020 PMT, thus the typical radiant sensitivity characteristic given in the Philips Photonics PMT catalogue [17] was used to get a relative quantum efficiency for different crystals. To make precise measurements, the 1 mm thick BGO crystal, calibrated in the experiment, was used as the reference. Fig. 7 shows the energy spectra of γ-rays from a ^{137}Cs source for several scintillators measured under the same XP2020 operating conditions. The positions of the full-energy peaks corrected for the integral quantum efficiency relative to that of the BGO crystal, indicate the relative light output, see column 4 of Table 10. This quantity is used sometimes to describe the light output of different crystals [9].

In the last column the light output measured by the "comparative method" is given. Note, the extremely good agreement (generally within ±5%) with the light output measured directly, see Table 9. Only the error of the measured light output for the CsI(Tl) crystal is somewhat higher (up to ±10 %). Note that the correction for the shaping time constant of 1.20 was made as in sect. V.*C.1*. The error of the method depends on the accuracy of the shape of the typical quantum efficiency characteristic of the PMT. This characteristic is better calibrated around 400 nm and worse at its long wavelength edge. And it is reflected in the less accurate measurement for the CsI(Tl) crystal. Since in fact the accuracy of the typical quantum efficiency characteristic is not well known, the accuracy of the proposed method is limited to about ±10 %. A better accuracy, of about ±5%, can be expected using a calibrated photomultiplier.

Table 10
Light output measurements using the comparative method

Crystal	Peak pos.,N [channel]$^{a)}$	Integral Q.E.$^{b)}$	Relative light output$^{c)}$	Light output [ph/MeV]
BGO	306	0.15	1	8060±120$^{d)}$
CsI(Tl)	1222	0.085	7.0	67700±6800
GSO	420	0.21	0.98	7900±800
LSO	1367	0.20	3.35	27000±2700
YAG	358	0.084	2.1	16900±1700
YAP	984	0.23	2.1	16900±1700
LuAP	631	0.23	1.35	10900±1100

a) Measured with the XP2020 PMT, no. 23495 having a Corning blue sensitivity according to Philips of 10.6 μA/lmF; the 3 μs shaping time constant was used in the amplifier.
b) Based on the typical radiant sensitivity characteristic of an XP2020 PMT [17]
c) The relative light output = $(N_{SC}/Q.E._{SC})/(N_{BGO}/Q.E._{BGO})$
d) The light output of the BGO crystal seen by the PMT, see Table 6

VII. CONCLUSIONS

The presented study proposes and confirms a procedure which allows the absolute light output of scintillators to be measured precisely. It is based on the measurement of small crystals, 9 mm in diameter and 1 mm thick for which the light collection is close to 100 %. The small diameter of the tested samples also assures full photoelectron collection when a PMT is used as the photosensor. The use of two different types of photosensors (Philips Photonics calibrated XP2020Q PMTs and Hamamatsu photodiodes) to measure light output has shown the importance of the crystal emission spectra, which currently seems to limit the accuracy of the light output determination, see CsI(Tl).

The absolute light output of BGO, CsI(Tl) and some Ce-doped new crystals was measured to an accuracy of about ±5%. The light output of the BGO crystal of 8500±350 ph/MeV agree well with the earlier measurement by Holl et al [2]. Thus a 9 mm diameter, 1 mm thick BGO crystal is proposed as a worldwide reference scintillator against which other scintillators of the same size can be compared.

And it has been shown that even a comparative method of measuring light output using an uncalibrated Philips XP2020 PMT and the proposed reference scintillator can provide an accuracy of ±10 %.

VIII. ACKNOWLEDGEMENTS

The authors are very indebted to Prof. Alex Lempicki from Boston University for suggesting to clear light output problem.

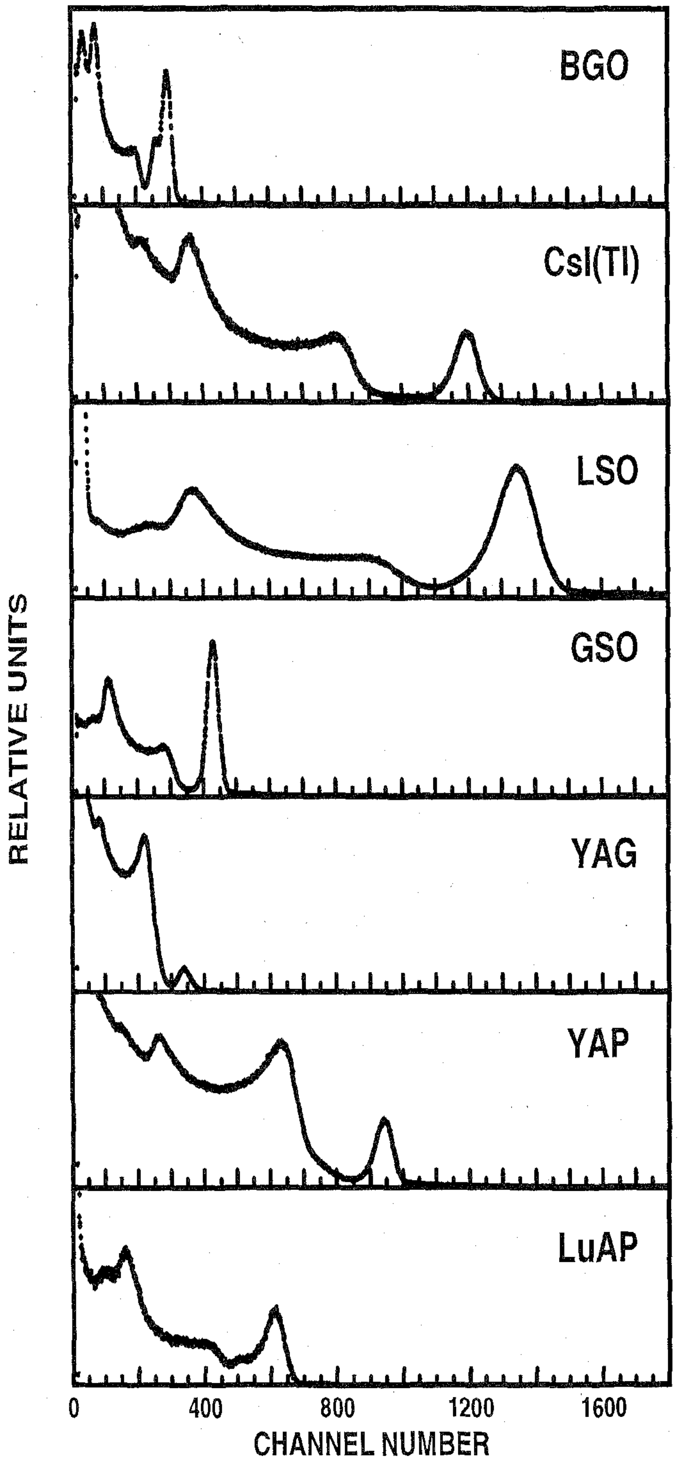

Fig. 7. A comparison of the energy spectra of γ-rays from a ^{137}Cs source measured with different scintillators to that of BGO.

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