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Measurement of absolute light yield and quantum efficiency of $LaBr_3$:Ce scintillator detector using SiPM

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Abstract: This brief communication presents our work to determine the absolute light yield and quantum efficiency of $LaBr_3$:Ce scintillator by comparison and also by direct pulse measurement method using SiPM. The first part presents use of the simpler comparison method to determine the light yields of different scintillators using the known yield of NaI(Tl) as reference. In the second part we have determined the absolute light yield and quantum efficiency of $LaBr_3$:Ce crystal by using a SiPM photo detector. Our measured value is in good agreement with the light yield reported by previous measurements using PMT and excitation fluorescence spectroscopy. Quantum efficiencies for scintillation detectors have been determined by using both PMTs and photo detectors, namely APDs by previous authors. This communication is possibly the first report on the determination of quantum efficiency of $LaBr_3$:Ce using SiPM photo detector. The simple and effective method presented here would allow to determine the light yield of any scintillation detector.

Keywords: Gamma detectors (scintillators, CZT, HPGe, HgI etc); Photoemission; Photon detectors for UV, visible and IR photons (solid-state) (PIN diodes, APDs, Si-PMTs, G-APDs, CCDs, EBCCDs, EMCCDs, CMOS imagers, etc); Scintillators, scintillation and light emission processes (solid, gas and liquid scintillators)

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2021 JINST 16 P12024

Contents

2021 JINST 16 P12024

1 Introduction

The light yield of a scintillation detector from absorption of a γ photon of given energy is one of its most important properties that determines its energy resolution and detection efficiency. One may also determine the Quantum Efficiency (QE) of conversion of deposited radiation energy to the total energy of the scintillation photons from the absolute light yield (number of scintillation photons generated) and the known emission spectrum of the emitted light. The measurement techniques for light yield can broadly be categorised in two groups, namely, comparative method and direct method. In method of comparison the light yield of a scintillator is determined by comparing the amplitude of its output signal with that of another scintillator with known light yield. However, in case of direct measurement the absolute light yield is determined without recourse to any known reference value. Here, the absolute yield of light photons is obtained by using suitable relation involving the values of the quantities, like, the output pulse height, the capacitance of the system, conversion efficiencies of the detector and photo-sensors (PMTs or photodiodes) etc. In addition to the pulse method, there are few other techniques also for direct measurements of the light yields of scintillators. For greater details of these methods we refer to [1]. Until the advent of photo detectors, the pulse height method involved use of PMTs as reported in the literature [2–5]. These authors reported about the light yield of different scintillators, like, NaI(Tl), CsI(Tl), BGO, BaF_2 etc. Miyajima et al. [2] have also measured the number of scintillating photons in plastic scintillators using PMT. There have also been useful supporting publications discussing the determination of yield of photoelectrons from the cathode, circuits for improved collection of the photoelectrons at the dynode etc. [2, 6]. Notwithstanding the importance of PMTs in nuclear instrumentation, there are also definite disadvantages in using PMTs for certain class of measurements. These drawbacks include the bulk size of PMTs, low quantum efficiency, inability to work in presence of magnetic field etc. Over the last three decades the traditional PMTs are being increasingly replaced by solid state photodetectors. Solid state photodetectors have distinct advantages over PMTs in terms of insensitivity to magnetic fields, reduced power consumption, reduced weight and size and insensitivity to temperature and voltage fluctuations. Some of the earliest attempts to measure light yield of scintillators using photodiodes have been reported in [3, 7–9]. Valentine et al. have studied the dependence of absolute scintillation yield on temperature for CsI(Tl) using silicon PIN photodiodes [7]. The regular photodiodes have led to the advent of Avalanche Photo Diodes (APDs) and more recently, SiPM. SiPMs have distinct advantages over PMTs in terms of internal gain, low noise and high quantum efficiency. The SiPM, made up of large number of microcells on a single substrate is characterised by very fast timing, very high gain (10^5 to 10^6 at low bias voltage) and very high quantum efficiency. The last two decades have seen a kind of explosive growth in the use of SiPM as photosensors for Scintillation detectors. Here we just refer to some of the recent and comprehensive reviews and references therein, discussing the usage and advantages of APDs and SiPM [10–12]. In this brief communication we report, possibly for the first time, use of SiPM for determination of the absolute light yield of $LaBr_3$:Ce crystal. The basic motivation of this work is two-fold. Firstly, the demonstration of a rather simple but accurate method to measure the absolute light yield and QE of any scintillator. Normally, majority of the experimentalists using scintillator detectors, get to know about these numbers from the manufacturers. A relatively limited number of groups involved in nuclear instrumentation are active in such measurements. Traditionally, these measurements have been carried out using PMTs which are associated with complications of exactly knowing the quantum efficiencies of the Photo cathode and successive dynodes. The use of solid state photo diodes, APDs and SiPM reduces the problem considerably. An important point to note is that, there have been very few measurements to determine QE using solid state sensors. To the best of our search, determination of QE using SiPM has not yet been reported. This technique is generic in nature and can be used for any scintillator. The selection of $LaBr_3$:Ce for the measurements is the second motivation for this work. The QEs of other time tested crystals like NaI(Tl), CsI(Na) etc. have been carried out using PMTs and solid state sensors, as cited by us. However, there have been very few reports on the determination of QE of $LaBr_3$:Ce using different techniques [13, 14, 18, 19]. Conti et al. [13] has employed the method described by M. Moszyinki et al. with PMT [3]. Loef et al. has measured the light yield/Mev for $LaBr_3$:Ce with different Ce^{3+} concentration using x-ray and γ-ray excitation fluorescence spectroscopy [14].The values reported in these papers are grossly close with significant variations (see table 3). The production of $LaBr_3$:Ce with much too superior properties opens up the possibility to have better understanding of the scintillation mechanisms. Knowledge of accurate values of QE and light yield may help the advanced large scale calculations to calibrate and tune themselves against the experimental data. In this context it is desirable to have some more measurements on the light yield. The following sections provide the experimental methods and discussions on the determination of absolute light yield of $LaBr_3$:Ce crystal.

2 Experimental details

2.1 Determination of relative light yields of different scintillators

The first part of the measurements involved determination of the relative light yields of a variety of scintillator detectors. This is basically a method of comparing the pulse heights of the different detectors for a given gamma ray energy when operated under same conditions of bias voltage, amplifier gain etc. Light output of any of the scintillator detectors can be estimated by comparing the pulse height with that of a reference detector with known light yield. In our work we have chosen the

2021 JINST 16 P12024

widely accepted value of light yield of NaI(Tl) as the reference. The different scintillators used were all cylindrical in shape and dimensions of $1'' \times 1''$ ($LaBr_3$:Ce and $CeBr_3$), and $2'' \times 2''$ (NaI(Tl), CsI(Na), BGO, CsI(Pure), NaI(Pure)). Each of the crystals was optically coupled to $2''$ diameter, ET-9266B PMT using DOW CORNING clear, transparent silicone fluid that matches the refractive indices well. Suitably designed Aluminium jigs were used for coupling the smaller $1''$ diameter detectors with the PMTs. The ET-9266B PMTs used in the measurements have ten dynode stages. We have used Active, home-made bases for the PMTs containing the voltage divider chain and charge sensitive preamplifier [15]. All the energy signals were drawn from the last dynodes and fed to the preamplifier. The preamplifier output was shaped and amplified by standard spectroscopic amplifier. In order to compare the pulse heights of the different detectors the PMT bias voltage

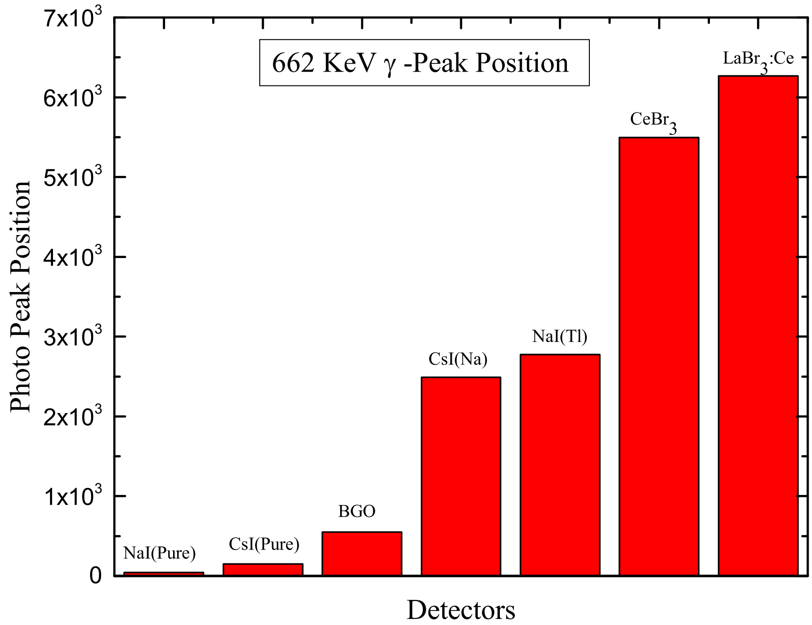

Figure 1. 662 γ ray Photo Peak Position from different scintillators.

and the gain of the spectroscopic amplifier were kept fixed for all the measurements. The output of the spectroscopic amplifier was digitised and recorded using 8k ADC. The pulse heights from all the detectors were compared using the 662 keV γ line from a ^{137}Cs radioactive source. Figure 1 shows the bar chart of photo peak positions of all the different scintillators. The pulse heights are expected to be proportional to the absolute light yield of the crystals. $LaBr_3$:Ce, as expected, shows the highest pulse height. We have chosen the well established light yield value of NaI(Tl) as the reference to derive the light yields for the other crystals. The values so derived are provided in table 1. These values are in fairly good agreement with the quoted values in literature and provides a good comparative study of the light yields. This rather simple method can always be the starting point to determine unknown light yields of scintillators with reference to a known value and can be reasonably accurate. However, this method can not substitute for more accurate absolute measurements. After the preliminary estimations of the light yields we attempted to measure absolute light yield using the same pulse method but with SiPM. The following section describes our efforts to determine the absolute light yield of $LaBr_3$:Ce using SiPM photo detector.

Table 1. Comparative photons yield/MeV for different inorganic scintillators.

Scintillator Detector	**662 keV γ-position**	**Photons per MeV**
NaI(Pure)	45	616
CsI(Pure)	152	2,082
BGO	550	7,537
CsI(Na)	2,490	34,121
NaI(Tl)	2,773	38,000
$CeBr_3$	5,496	75,314
$LaBr_3$:Ce	6,267	85,880

2.2 Measurements of absolute light yield and quantum efficiency of $LaBr_3$:Ce crystal using SiPM

The measurements were carried out using a cylindrical $LaBr_3$:Ce scintillator crystal of diameter 25.4 mm and thickness of 25.4 mm manufactured by Saint Gobin Inc. The crystal is encapsulated in 0.5 mm thick Al casing with a glass window on one of the ends. The photo detection was achieved by using 6 mm × 6 mm SensL B-series (60035) SiPM having 18,980 microcells with each measuring 35 µ. The detailed specifications of the SensL SiPM are given in table 2. The SiPM was mounted on a home-made printed circuit board (PCB), designed using OrCAD[1] software for read out signal. The mounted SiPM was placed at the centre of the glass window of the detector. The remaining portion of the window can possibly be covered with reflecting tyvek paper. However, the reflectivity may not be hundred percent and can cause uncertainties in the measurement. de Haas et al. have reported about uncertainties in determination of light yield using PMT unless back reflection is properly accounted for [16]. In our measurements we used thick black paper for complete absorption of scintillating photon that fell outside the surface of the SiPM. This means that the final pulse height is generated only by the photons impinging upon the SiPM surface. We have used proper geometric correction factor, as will be discussed later, to arrive at the total number of photons falling upon the entire glass surface. The whole assembly of the crystal and the SiPM mounted on the PCB was tightly wrapped with black insulation tape to avoid any light leak. The light reflected back from the surface of the SiPM is expected to return to the SiPM after internal reflections in the detector volume. Considering the rather small volume of the detector the attenuation is assumed to be insignificant compared to other uncertainties. In fact, it has been shown by Nemallapudi et al. that there are no serious effect of angular response for simple configurations of detector and SiPM [17]. Figure 2 provides the photos of the PCB, the SiPM and the final assembly. The SiPM was reverse biased with 30 V with over voltage of about 5 V. The output signal (V_0) for 662 keV γ-rays was measured on a LeCroy 1 GHz digital oscilloscope.

3 Analysis and discussion

One can calculate the number of electron-hole pairs created in the SiPM and eventually the absolute light yield of the detector from the value of the output signal voltage, the capacitance of the detection

[1] http://www.orcad.com/.

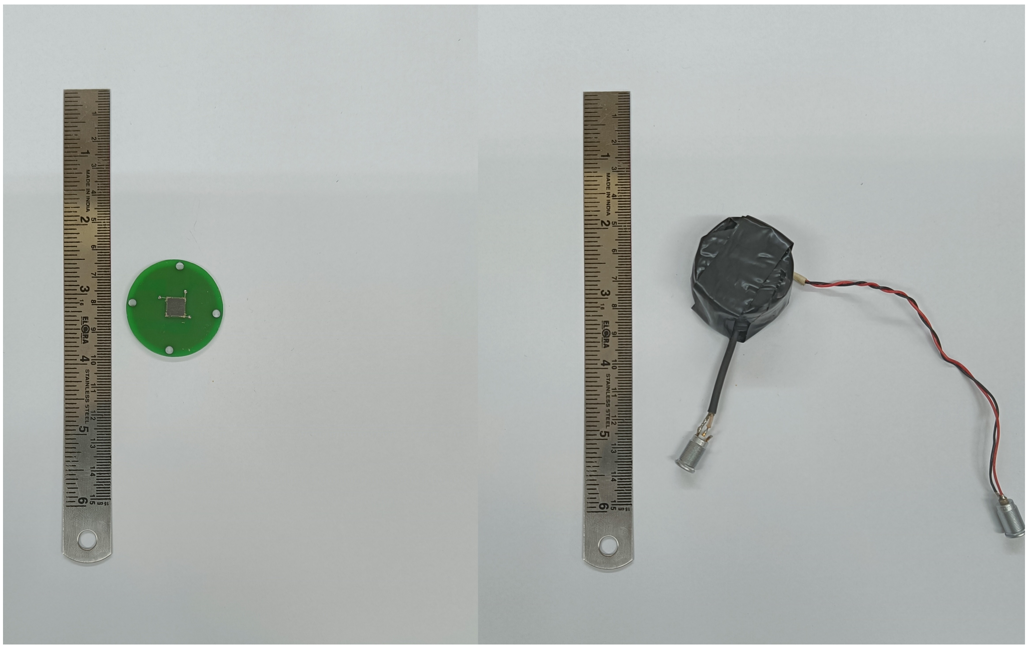

Figure 2. (On left) SiPM mounted on PCB, (on right) whole assembly covered with black tape.

system and all necessary correction factors. The equation for the light yield is given by

$$N_p = \frac{CV_0}{e}\frac{k}{G}\frac{1}{\epsilon_0}\frac{1}{FF} \tag{3.1}$$

where, N_p is light yield for deposition of 662 keV γ photon, V_0 is the measured output voltage

Table 2. Specification of the SensL SiPM used in this work.

SiPM Specification	
SiPM series	SensL B-60035
No. of Micro cells	18,980
Active area	$6 \times 6\,\text{mm}^2$
Fill Factor (FF)	64 %
Average Photo Detection Efficiency (ϵ_0)	29.9 %
Breakdown voltage	25 V
Gain at over voltage 5 V (G)	4.3×10^4
Capacitance of SiPM	51 pF
Capacitance of Cable	31 pF

(34 ± 2 mV), $C = 102$ pF is the combined capacitance of the detection system comprising the SiPM, the cable and the oscilloscope (see table 2), e is the electronic charge, G is the internal gain of SensL B-series SiPM after dark current consideration and is given by 4.3×10^4 [12], FF is the fill factor of SiPM (64%) and ϵ_0 is photo detection efficiency (PDE) of SiPM. The PDE of the SiPM is 29 % at 380 nm. However, in our calculation we have considered the known spectral distribution of PDE of the SiPM and have estimated an average value of 29.9 %. The multiplicative

2021 JINST 16 P12024

factor k is the geometric factor (as mentioned earlier) and is the ratio of the surface areas of the crystal and the SiPM. The number of photons produced corresponding to 662 KeV γ ray came out to be $N_p = 38{,}185$. This in turn, yields the total number of photons per MeV gamma rays to be 55,954 ± 3392. The error is estimated by considering the uncertainties associated with the different factors in the formula. Assuming the most probable peak value of 380 nm for the spectral distribution of $LaBr_3$:Ce scintillation photons the quantum efficiency for deposition of 1 MeV of γ energy comes out to be around 18.8 %. However, we have considered the known spectral distribution of emission of scintillation photons of $LaBr_3$:Ce to estimate the total scintillation energy produced for the extracted light yield. The efficiency comes out to be 18.52 % and is in good agreement with what has been reported by M. Conti et al. [13] and Loef et al. [14] for $LaBr_3$:Ce. Table 3 summarises the value obtained by us and the previous measurements [13, 14, 18, 19].

Table 3. Measured light yield of $LaBr_3$:Ce.

Author	**Absolute light yield / MeV**
M. Conti et al. [13]	57,700 ± 2900
Loef et al. [14]	61,000 ± 5000
W. Chewpraditkul *et al.* [18]	42,500 ± 4000
K.S. Shah et al. [19]	60,000
This Work	55,954 ± 3392

4 Conclusion

The absolute light yield and quantum efficiency is one of the most important properties of a scintillation detector. These values are generally reported by the manufacturers and relatively fewer number of users using specialised optical/fluorescence techniques and associated equipment. In this work we have tried to determine the light yield of $LaBr_3$:Ce scintillator using two relatively simpler methods. The first method determines the light yield by comparing the output pulses from different scintillators with the known yield of NaI(Tl). The second method uses SiPM photo detector to extract absolute light yield and quantum efficiency of $LaBr_3$:Ce crystal. Our measured value is in general agreement with the light yield determined by other groups, using PMTs and X-ray excited optical fluorescence method. This communication is possibly the first report on the determination of quantum efficiency of $LaBr_3$:Ce using SiPM photo detector. In summary, the importance of this work is two-fold. Firstly, it demonstrates a simple but accurate method for measuring absolute light yield of scintillators, in general. Secondly, it measures the absolute light yield of $LaBr_3$:Ce for which there have been very limited number of measurements using different techniques.

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2021 JINST 16 P12024