Spectral Response of UV Photodetectors for Barium Fluoride Crystal Readout

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Abstract—Because of its fast scintillation peaked at 220 nm with decay time of less than 0.6 ns barium fluoride crystals have attracted a broad interest in the community pursuing ultrafast detectors for future HEP experiments and GHz hard X-ray imaging for future XFEL facilities. A crucial issue for its application is the spectral response of photodetectors down to VUV. In this paper, we compare quantum efficiency and photon detection efficiency spectra measured for several UV photodetectors down to 200 nm. Their figures of merit on the detection efficiency for the fast component and the suppression of the slow component are also discussed.

I. INTRODUCTION

BECAUSE of its fast cross-luminescence [1-7] peaked at 220 nm with decay time of less than 0.6 ns [8-15] barium fluoride (BaF_2) crystals have attracted a broad interest in the community pursuing ultrafast calorimetry for future high energy and nuclear physics experiments [14,19] and for GHz hard x-ray imaging for future X-ray Free Electron Laser (XFEL) facilities [9,13]. One crucial issue preventing BaF_2 application is its slow scintillation component peaked at 300 nm due to self-trapped excitons with decay time of 600 ns and an intensity of more than five times of the fast component, which causes pileup and readout noise in a high-rate environment.

A BaF_2 crystal calorimeter was baselined for the Mu2e experiment [14] and was replaced by an undoped CsI crystal calorimeter mainly due to this slow component [15]. It is also well known that undoped CsI survives the Mu2e radiation environment where an ionization dose up to a few tens krad but not a few hundred krad expected by Mu2e-II. BaF_2 , on the other hand, is found more radiation hard against an ionization dose up to 200 Mrad [16], a proton fluence up to 1×10^{15} p/cm² [17] and a neutron fluence up to 9×10^{15} n_{eq}/cm² [18]. To cope with the unprecedented event rate, a BaF_2 crystal-based ultrafast calorimeter is proposed for the Mu2e-II experiment [19]. One crucial issue is the pile-up and readout noise caused by the slow component. R&D has been going-on along two directions to address this issue. One is selective rare earth or transition metal doping in BaF_2 crystals [20-32]. The other is to use solar-blind photodetectors sensitive only to the fast component at 220 nm but not the slow component at 300 nm [27, 33-35].

Progresses have been achieved along both directions. Fig. 1 shows X-ray excited emission spectra measured for BaF_2 crystal samples with different yttrium doping level, showing consistent fast scintillation component, and significantly suppressed slow component with increased yttrium doping level [31]. Recent investigation also shows that solar-blind UV photodetectors are needed to further suppress the slow component and reduce radiation induced readout noise to a level of less than 1 MeV for BaF_2 crystals of Mu2e size [36]. In this paper, we report quantum efficiency (QE) and photon detection efficiency (PDE) spectra measured for several UV/VUV photodetectors down to 200 nm. Their figure of merit on the detection efficiency for the fast component and the slow component suppression is also discussed.

Fig. 1 X-ray excited emission spectra measured for BaF_2 crystal samples with different yttrium doping level [31].

II. EXPERIMENTAL SETUP AND PHOTODETECTORS

Fig. 2 shows a test bench used to measure QE and PDE as a function of wavelength. An UV extended 150 W Xenon lamp was used as the light source. The fluctuation of the light source intensity was monitored by a photodiode mounted on the lamp

Manuscript received Dec 12, 2021. This work was supported by the U.S. Department of Energy, Office of High Energy Physics program under Award No. DE-SC0011925.

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house and corrected for through a lock-in amplifier (Stanford Research Systems SR810). A narrow wavelength band was selected by a monochromator, chopped by an optical chopper, and coupled to a 1 mm quartz fiber with NA = 0.22. The light pulses from the fiber were centered to a $\Phi 5$ mm area of the photodetector to be measured. The response of the photodetector was scanned from 200 to 800 nm and was readout through a low noise pre-amplifier (Newport 70710) and the lock-in amplifier.

Fig. 2 A setup used to measure QE and PDE as a function of wavelength.

For photodetectors with a unit gain, their $QE(\lambda)$ is obtained by normalizing its response $R(\lambda)$ to the response of a NIST traceable reference Si-PD (Newport 71650) $R_{PD}(\lambda)$ scanned under the same settings, as shown in Eq. 1:

$$QE(\lambda) = \frac{R(\lambda)}{R_{PD}(\lambda)} QE_{PD}(\lambda) \quad (1)$$

The QE of four Hamamatsu R2059 PMTs and a Photek solar-blind photo-cathode diode was measured, where a home-made socket connected all dynodes to set their gain to one.

Fig. 3 SiPM output pulse (red) to 10 ns pulse from a 465 nm blue LED is shown in an 800 ns gate (blue dots) for pulse height spectra.

For photodetectors with gain, such as SiPM, the normalized response $R(\lambda)$ is a product of the PDE and the gain, so is a relative PDE. The calibration of SiPM PDE was carried out by

using a 465 nm blue LED. Fig. 3 shows a scope trace of SiPM response (red) to LED pulses of 10 ns FWHM. The charge of the SiPM output pulses was integrated by a LeCroy 3001 qvt in 800 ns gate (blue dots) and digitized for a pulse height spectrum.

Figs. 4 and 5 show the pulse height spectra measured by two FBK R&D SiPMs, sn612-A1 and sn615-A1, integrated with UV filters I and II respectively with breakdown voltages of 25.0 V and 31.5 V. Also shown in the figures are the numerical values of the position and widths of photopeak and pedestal.

Fig. 4 The pulse height spectrum of a FBK SiPM (612-A1, $V_{br}=25.0$ V) with UV filter I measured by using 10 ns light pulse from a 465 nm LED.

Fig. 5 The pulse height spectrum of FBK SiPM (615-A1, $V_{br}=31.5$ V) with UV filter II measured by using 10 ns light pulse from a 465 nm LED.

The photoelectron (p.e.) number of the photopeak was calculated according to Eq. 2.

$$N_{p.e.} = \frac{(P_{LED} - P_P)^2}{\sigma_{LED}^2 - \sigma_P^2} \quad (2)$$

where P_{LED} and σ_{LED} are the LED photo-peak and width, P_P and σ_P are the pedestal peak and width. The photoelectron number was determined as 123.5 and 152.3 for these two FBK SiPMs, respectively.

The input photon number from LED pulses was determined by measuring the DC current by a reference Si-PD with known QE according to Eq 3.

$$N_{ph} = \frac{I_{PD}/S}{h\nu_{LED} \times f_{LED}} \quad (3)$$

where I_{PD} and S are the photocurrent and sensitivity of the reference Si-PD, $h\nu_{LED}$ and f_{LED} are the LED photon energy and the pulse rate.

The PDE value at 465 nm was determined as Eq. 4.

$$PDE(465 \text{ nm}) = \frac{N_{p.e.}}{N_{ph}} \quad (4)$$

The σ_{LED} , obtained from the Gaussian fitting, however, is affected by the excess noise factor (ENF) of the photodetector. A cross-check was carried out by measuring the response of a Hamamatsu R2059 PMT with a gain provided by a normal base socket. The resultant ENF was found to be about 1.1, which is consistent with Hamamatsu technical note. The ENF values for SiPMs were also measured. Fig. 6 shows that individual photon electron peaks can be clearly resolved in SiPM response to attenuated LED pulses by using an amplifier (Ortec VT120) and digitizer (CAEN V1720). The ENF values were determined as the ratio between the photoelectron numbers from this single p.e. calibration to that from Eq. 2.

Fig. 6 Individual photo electron peaks observed by a FBK SiPM its responding to attenuated LED pulses.

After the ENF correction shown in Eq. 5, the PDE values at 465 nm are 6.3% and 35.1% for two FBK SiPMs with Type I and II filters, respectively.

$$PDE(465 \text{ nm}) = \frac{N_{p.e.}}{N_{ph}} \times ENF \quad (5)$$

The PDE of four Hamamatsu MPPCs (or SiPMs) and several FBK R&D SiPMs with integrated UV filter was obtained by using the relative PDE $R(\lambda)$ from 200 to 600 nm and the 465 nm calibration.

III. RESULTS AND DISCUSSION

Fig. 7 shows consistent QE spectra between 200 and 700 nm for four Hamamatsu R2059 PMTs.

Fig. 7 The measured QE (200-700 nm) of four Hamamatsu R2059 PMTs.

Fig. 8 The measured QE (200-400 nm) of a Hamamatsu R2059 PMT and the X-ray excited emission spectra of BaF_2 and $BaF_2:Y$.

Fig. 8 shows the measured QE spectrum (red dots with error bars) between 200 and 400 nm for a R2059 PMT and the X-ray excited emission spectra of BaF_2 (black solid lines) and $BaF_2:Y$ with suppressed slow emission (black dashed lines). Also shown in the figure are the numerical values of the emission weighted QE (EWQE) defined as:

$$EWQE_{fast\ or\ slow} = \frac{\int_{\lambda_1}^{\lambda_2} Em(\lambda)QE(\lambda)d\lambda}{\int_{\lambda_1}^{\lambda_2} Em(\lambda)d\lambda} \quad (6)$$

where $Em(\lambda)$ is the x-ray excited emission spectrum of BaF_2 or $BaF_2:Y$, and $\lambda_1=200$ and 250 nm and $\lambda_2=250$ and 400 nm respectively for the fast and slow light. The $EWQE_{fast}$ and $EWQE_{slow}$ values are 15.2% and 20.9% respectively for the fast and slow light. Since the emission spectra of BaF_2 and $BaF_2:Y$ have a similar line shape (with different intensity for the slow light) the corresponding emission weighted QE values are the same for both BaF_2 and $BaF_2:Y$. Also shown in the figure are the ratio between the fast and the slow scintillation light (F/S) for BaF_2 and $BaF_2:Y$, which are defined as:

$$F/S = \frac{\int_{200nm}^{250nm} Em(\lambda)QE(\lambda)d\lambda}{\int_{250nm}^{400nm} Em(\lambda)QE(\lambda)d\lambda} \quad (7).$$

The $EWQE_{fast}$ and the F/S ratio are considered as the figures of merit representing photodetector's ability for the fast detection and the slow suppression, respectively. While the $EWQE_{fast}$ values are 0.15 for both BaF_2 and $BaF_2:Y$, their F/S ratio values are 1/7 and 1/2.1 respectively for the Hamamatsu R2059, indicating a factor of 3.5 improvement in the slow suppression provided by $BaF_2:Y$.

Fig. 9 The measured QE (200-400 nm) of Photek solar blind photocathode and the X-ray excited emission spectra of BaF_2 and $BaF_2:Y$.

Fig. 9 shows the measured QE between 200 and 400 nm for the Photek solar blind photocathode. The $EWQE$ for fast and slow components are 25.6% and 10.6% respectively, showing a high detection efficiency and a clear selective readout for the fast component. While the $EWQE_{fast}$ values are 0.26 for both BaF_2 and $BaF_2:Y$, the F/S values are 1/0.6 and 1/ 2.1, indicating once again a factor of 3.5 better slow suppression for $BaF_2:Y$. Compared to the bi-alkali cathode of Hamamatsu 2059 shown in Fig. 10, the Photek solar-blind cathode shows a factor of 1.5

better efficiency for fast detection and another factor of 3.5 better for slow suppression.

Fig. 10 The measured PDE (200-800 nm) of the Hamamatsu VUV3 MPPC (S13371-6621-A1, $V_{br}=51.0$ V) at operation voltage of 53, 55 and 57 V.

Fig. 10 shows PDE for the Hamamatsu VUV3 MPPC S13371-6621-A1 ($V_{br}=51.0$ V) between 200-800 nm with three operation voltage of 53 (blue), 55 (red) and 57 (green) V. Also shown in the figure is the 465 nm blue LED calibration at the nominal operating voltage 55 V.

Fig. 11 The measured PDE (200-400 nm) of the Hamamatsu VUV3 MPPC and the X-ray excited emission spectra of BaF_2 and $BaF_2:Y$.

Fig. 11 shows PDE between 200 and 400 nm for the Hamamatsu VUV3 MPPC S13371-6621-A1 at the nominal operating voltage 55.0 V. Its low $EWQE_{fast}$ values of 0.10 indicates a low detection efficiency for the fast component. Its F/S values are 1/4.8 and 1/1.5 respectively for BaF_2 and $BaF_2:Y$

crystals respectively, indicating a factor of 3.2 better slow suppression for BaF₂:Y. Compared to PMTs, its F/S ratio is better than bi-alkali cathode (R2059), but worse than Photek solar-blind cathode.

Fig. 12 The measured PDE (200-600 nm) of FBK SiPM sn:612-A1 with the UV filter I at operation voltage of 27.5, 29.0 and 30.5 V, $V_{br}=25.0$ V.

Fig. 12 shows measured PDE spectra between 200 and 600 nm for the FBK SiPM integrated with the type I UV bandpass filter (sn:612-A1, $V_{br}=25.0$ V) at operation voltage of 27.5, 29.0 and 30.5 V. Also shown in the figure is the 465 nm blue LED calibration done at the nominal operating voltage 29 V.

Fig. 13 The measured PDE (200-400 nm) of the FBK SiPM 612-A1 at 30.5V and the X-ray excited emission spectra of BaF₂ and BaF₂:Y.

Fig. 13 shows its PDE (200-400 nm) at 30.5V and the X-ray excited emission spectra of BaF₂ and BaF₂:Y. The emission weighted photon detection efficiencies (EWPDE) are 17.8%

and 12.7% for the fast and slow component. The figures of merit are 0.18 for the fast component detection and 1/3.6 and 1/1.1 for the F/S ratio for BaF₂ and BaF₂:Y respectively, indicating a promising solution for slow suppression. R&D will be continued along this direction.

Fig. 14 The measured PDE (200-600 nm) of FBK SiPM sn:615-A1 with the UV filter II at operation voltage of 34.0, 35.5 and 37.0 V, $V_{br}=31.5$ V.

Fig. 14 shows the measured PDE spectra between 200 and 600 nm for the FBK SiPM integrated with the type II UV filter (sn:615-A1, $V_{br}=31.5$ V) at operation voltage of 34.0, 35.5 and 37.0 V. The observed oscillation is consistent with the filter design. Also shown in the figure is the 465 nm blue LED calibration at the nominal operation voltage 35.5 V.

Fig. 15 The measured PDE (200-400 nm) of the FBK SiPM 615-A1 at 37.0 V and the X-ray excited emission spectra of BaF₂ and BaF₂:Y.

Fig. 15 shows its PDE (200–400 nm) spectrum at 37V and the X-ray excited emission spectra of BaF₂ and BaF₂:Y. The spectral response shows no additional slow suppression with this type of UV filter. R&D will not be continued along this direction.

Table I summarized the numerical values for the photodetectors investigated. The first two columns are EWQE/EWPDE for the fast and the slow component. The third and fourth ones are the fast/slow ratio for BaF₂ and BaF₂:Y crystals, where the slow suppression effect of BaF₂:Y is shown. While the EWQE/EWPDE is directly related to the light output from a photodetector, the F/S ratio represents its ability for slow suppression. A combination of BaF₂:Y crystals and selective readout provided by solar-blind photodetectors from either Photek photocathode or FBK SiPM integrated with the type-I UV bandpass filter shows a promising solution.

TABLE I. SUMMARY OF THE FIGURES OF MERIT FOR PHOTODETECTORS

Photodetectors	EWQE _{fast} (%)	EWQE _{slow} (%)	BaF ₂ F/S	BaF ₂ :Y F/S
Hamamatsu R2059 PMT	15.2	20.9	1/7.0	1/2.1
Hamamatsu MPPC S13371	10.5	9.8	1/4.8	1/1.5
Photek PMT	25.6	10.6	1/2.1	1/0.6
Solar blind				
FBK SiPM	17.8	12.7	1/3.6	1/1.1
w/UV filter-I				
FBK SiPM	20.7	31.5	1/7.8	1/2.4
w/UV filter-II				

IV. SUMMARY

While yttrium doping in BaF₂ crystals increases the F/S ratio by a factor of three, solar-blind photodetectors would further reduce pileup noise for a BaF₂ crystal based ultrafast calorimeter for future HEP experiments, such as Mu2e-II. Progresses have been made in both solar-blind photocathode and SiPMs with integrated UV band-pass filter. R&D is ongoing to further optimize the EWQE/EWPDE_{fast} and the F/S ratio for BaF₂ crystal readout with photodetectors.

Since a fraction of BaF₂ emission is below 200 nm we plan to extend the coverage of our QE/PDE test bench to the VUV range down to 175 nm with either vacuum or N₂ purging. Novel VUV photodetectors, such as the Hamamatsu SiPM investigated in this manuscript and other semiconductor-based VUV photodetectors [37, 38] will also be investigated.

ACKNOWLEDGEMENTS

The authors are grateful to Dr. P. Hink for providing the solar-blind photocathode investigated in this work.

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