# Recent Progress of Large Size $BaF_2$:Y Crystals for Future HEP Experiments

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***Abstract*–Because of its ultrafast light with sub-ns decay time and the suppressed slow scintillation light yttrium doped barium fluoride ($BaF_2$:Y) crystals attract a broad interest in the community pursuing ultrafast detector technology. $BaF_2$:Y crystals of large size were grown for the proposed Mu2e-II calorimeter. Their scintillation performance, such as transmittance, light output, and fast/slow ratio, was characterized. Gamma-ray induced readout noise was found to be dominated by the slow scintillation component in $BaF_2$ crystals.**

## I. Introduction

$BaF_2$ crystals with sub-ns scintillation peaked at 220 nm are promising for ultrafast calorimetry for future HEP experiments facing unprecedented event rate, such as the proposed Mu2e-II calorimeter. Its slow scintillation peaked at 300 nm, however, would cause pile-up for such an application. Two approaches have been taken to suppress the slow signal for the Mu2e-II $BaF_2$ calorimeter: 1) selective doping in $BaF_2$ to suppress the slow scintillation component and 2) using solar-blind photodetector with a higher sensitivity to the fast component than the slow component. In the last several years, yttrium doped barium fluoride ($BaF_2$:Y) crystals were found to feature with effectively suppressed slow light and unchanged ultrafast light. R&D is on-going to optimize yttrium doping uniformity and radiation hardness for $BaF_2$:Y crystals of calorimeter size.

We report optical and scintillation properties measured for two $BaF_2$:Y crystals grown by BGRI and SIC in 2020, as well as γ-ray induced readout noise (RIN:γ) under 2 and 23 rad/h, which are expected by the Mu2e and Mu2e-II calorimeters.

## II. Experimental Details

Fig. 1 shows two $BaF_2$:Y crystals of 25×25×200 $mm^3$ grown by BGRI (top) and SIC (bottom). Transmittance spectra were measured by using a PerkinElmer Lambda 950 spectrophotometer with 0.15% precision. Light output was measured by using a Hamamatsu R2059 photomultiplier tube (PMT) with a grease coupling to the crystal excited by 0.511-MeV γ-rays from a $^{22}$Na source with a coincidence trigger. The systematic uncertainty of the light output is about 1%. RIN:γ was measured by using a similar setup used to measure RIN:γ for BTL LYSO bars [1]. $BaF_2$:Y crystals wrapped by Tyvek paper with an air gap coupled to a Hamamatsu PMT R2059, were irradiated by Co-60 γ-rays under dose rates of 2 and 23 rad/h.


Fig. 1. Two $BaF_2$:Y crystals grown by BGRI with a dimension of 25×25×201 $mm^3$ (top) and SIC with a dimension of 25×25×197 $mm^3$ (bottom) for the Mu2e-II experiment.

## III. Results and Discussion

Fig. 2 shows their longitudinal transmittance (solid lines) and x-ray excited emission (blue dashes) spectra for BGRI (top) and SIC (bottom) samples. Both samples show reduced absorption as compared to previous samples, indicating a better control on impurities and defects. Also shown in Fig. 2 is the theoretical limit of transmittance (blue dots) calculated assuming no internal absorption. The BGRI sample approaches the limit, indicating no scattering centers.

Fig. 3 shows light output as a function of integration time with consistent fast component ($A_0$) of about 100 p.e./MeV and the fast/slow ratio (F/S or $A_0/A_1$) of 0.64 and 1.1 for the BGRI (top) and SIC (bottom) samples, respectively.

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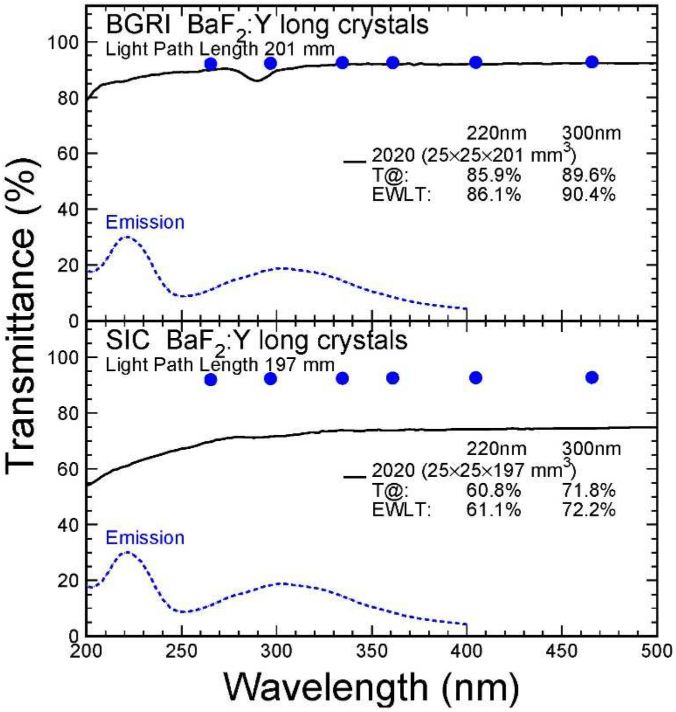


Fig. 2. Longitudinal transmittance (solid lines) and x-ray excited emission (blue dashes) spectra are shown for BGRI (top) and SIC (bottom) samples. Also shown is the theoretical limit of transmittance (blue dots).

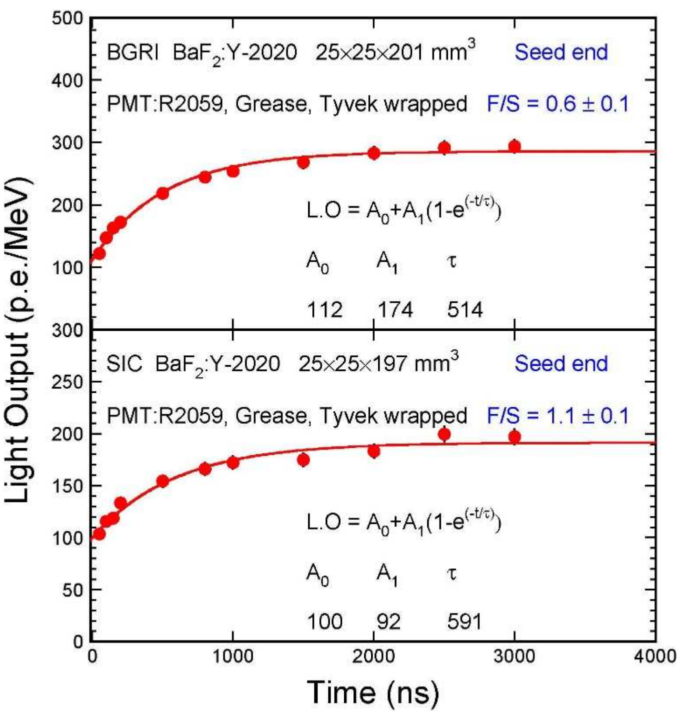


Fig. 3. Light output is shown as a function of integration time for BGRI (top) and SIC (bottom) $BaF_2$:Y samples.

Fig. 4 shows photocurrent history before, during and after Co-60 γ-ray irradiation of about 1 minute with a dose rate of 23 rad/h for the SIC $BaF_2$:Y sample (top) and an SIC undoped $BaF_2$ sample (bottom) of $30\times30\times250$ mm$^3$. Photocurrent of 63 and 104 μA was measured by the PMT under 1,100 and 900 V bias respectively for the $BaF_2$:Y and $BaF_2$ samples during irradiation, showing a much-reduced photocurrent in $BaF_2$:Y. The phosphorescence (afterglow) shows a 40 and 10 second fast decay time for the $BaF_2$:Y and $BaF_2$ samples respectively, and a consistent 300-second-long decay time. Yttrium doping is found to increase the afterglow with fast decay from 70% to 88.5% and reduce the slow 300 second decay component from 30% to 11.5%.

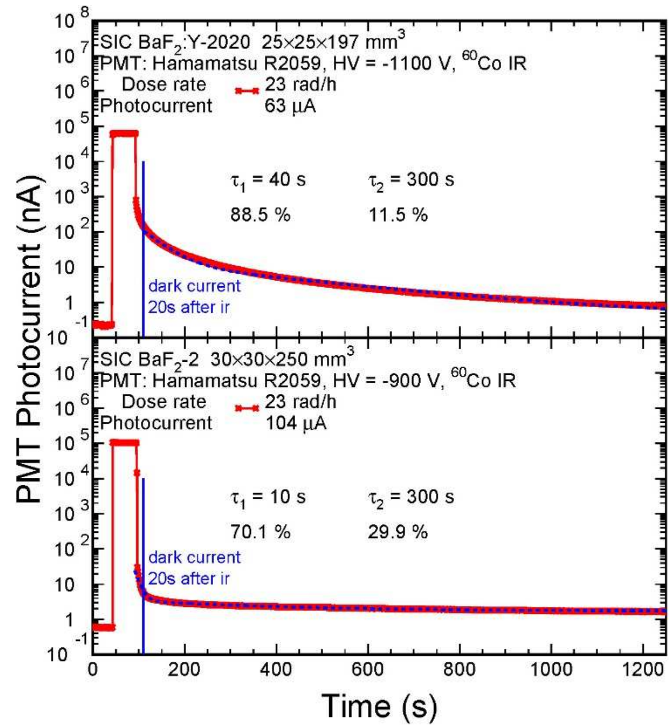


Fig. 4. Photocurrent measured by a Hamamatsu R2059 PMT for SIC $BaF_2$:Y (top) and SIC $BaF_2$ (bottom) samples before, under 23 rad/h Co-60 γ-ray irradiation of 1 minute and after irradiation.

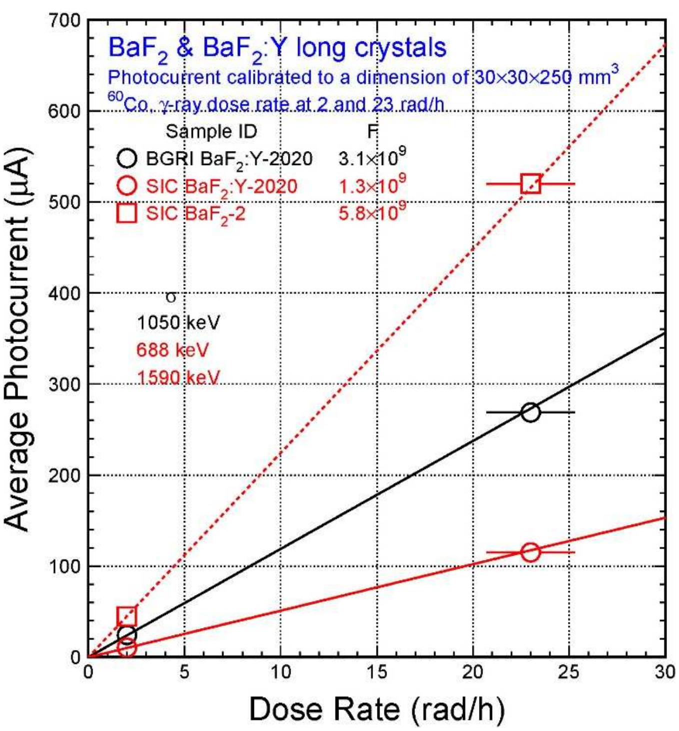


Fig. 5. Photocurrent is shown as a function of the dose rate for the BGRI and SIC $BaF_2$:Y and a SIC undoped $BaF_2$ samples under 2 and 23 rad/h.

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Fig. 5 shows the average PMT photocurrent during irradiation as a function of the dose rate for two $BaF_2$:Y and an undoped $BaF_2$ samples under 2 and 23 rad/h. An excellent linearity was observed between the γ-ray induced photocurrent and the dose rate. Yttrium doping in $BaF_2$ reduces the γ-ray induced photocurrent and readout noise significantly. The γ-ray induced photocurrent in $BaF_2$:Y and $BaF_2$ samples was also found to be highly correlated to the slow component ($A_1$), indicating that the slow scintillation component dominates the γ-ray induced photocurrent and readout noise.

## IV. Summary

$BaF_2$ crystals provide ultrafast light with 0.5 ns decay time. Yttrium doping increases the F/S ratio while maintaining the ultrafast light unchanged, promising an ultrafast calorimeter with much-reduced pile-up. Two recent $BaF_2$:Y long crystals grown by BGRI and SIC show much-reduced impurity related absorption, a consistent fast component of 100 p.e./MeV, and a fast/slow ratio of 0.6 and 1.1, respectively for the BGRI and SIC samples. RIN:γ was measured for two $BaF_2$:Y samples and an undoped $BaF_2$ crystal samples under 2 and 23 rad/h. Gamma-ray induced readout noise is dominated by the slow scintillation component.

## References

[1] C. Hu *et.al,* "Gamma-Ray- and Neutron-Induced Photocurrent and Readout Noise in LYSO+SiPM Packages," IEEE Trans. Nucl. Sci., vol. 68, no. 6, pp. 1244-1250, June 2021.

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