Development of BaF_2 Crystals for Future HEP Experiments at the Intensity Frontiers

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***Abstract*– Barium fluoride (BaF_2) is a fast inorganic crystal scintillator. Because of its fast scintillation with sub nanosecond decay time it is considered as a candidate crystal for a very fast crystal calorimetry for future HEP experiments at the intensity frontier. Two crucial issues of BaF_2 application are its radiation hardness and its slow scintillation component with 600 ns decay time, which causes pile-up. BaF_2 crystals produced by different vendors were irradiated by γ-rays up to 120 Mrad, and show good radiation hardness. A 20 cm long rare earth doped BaF_2 crystal grown by BGRI shows promising performance in slow component suppression.**

I. INTRODUCTION

BARIUM fluoride (BaF_2) crystal has a very fast scintillation component peaked at 220 nm with sub-ns decay time, which provides a good foundation for a very fast calorimetry to face the challenge of the unprecedented high event rate expected in future HEP experiments at the intensity frontier. It was proposed to build a precision electromagnetic calorimeter for Higgs searches for the proposed SSC back in nineties [1-3], and was the baseline option for the Mu2e experiment at Fermilab [4]. BaF_2, however, has also a slow scintillation component peaked at 300 nm with 600 ns decay time and five times brightness of its fast scintillation component, which leads to a serious pile-up effect [5-8]. To mitigate this pile-up effect, it is necessary to suppress the slow component. Two approaches may be used: (1) selective doping with rare earth (RE, La, Y, and Ce etc.) in BaF_2 crystals [9-12] and (2) selective readout with solar blind photodetector, which is sensitive to the fast component peaked at 220 nm and not sensitive to the slow component peaked at 300 nm [7].

The investigations reported here were carried out to understand three key issues: performances, radiation hardness and slow suppression for large size pure and RE doped BaF_2 crystals. All samples are obtained from three vendors: BGRI, Incrom and SIC.

II. PERFORMANCES AND RADIATION HARDNESS OF PURE BARIUM FLUORIDE CRYSTAL

A total of twenty five pure BaF_2 crystals were characterized. Three BGRI crystals are of $3\times3\times20$ cm^3, two Incrom crystals are of $3\times3\times20$ cm^3, and twenty SIC crystals are of $3\times3\times25$ cm^3.

Fig. 1 shows longitudinal transmittance (LT) for three BaF_2 crystal samples from BGRI, Incrom and SIC. All of them approach the theoretical limit between 400-800 nm (black dots), indicating very good optical quality. Also shown in the figure are the numerical values of the emission weighted longitudinal transmittance (EWLT) for the fast (200 nm) and slow (300 nm) scintillation components.

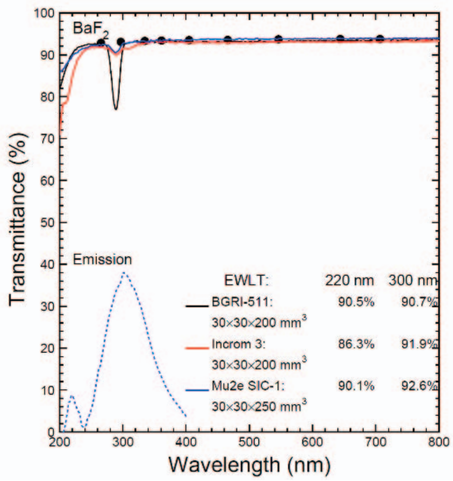

Fig. 1 Longitudinal transmittance of BaF_2 crystals from three vendors.

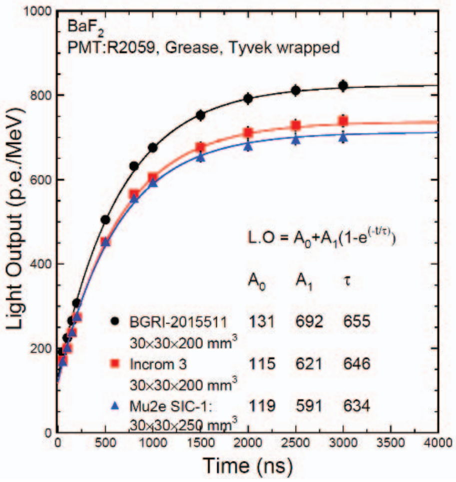

Fig. 2 Light output is shown as a function of integration time for BaF_2 crystals from three vendor.

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Fig. 2 shows light output as a function of integration time for BaF_2 crystals from three vendors. More than 100 p.e./MeV was observed in the fast component for all samples. A relatedly low light output was observed in the SIC sample because of its length.

Fig. 3 shows light output as a function of distance to the photodetector for three BaF_2 crystals from different vendors. This light response uniformity (LRU) distribution was measured by aiming a Na-22 γ-ray source at seven points evenly distributed along the crystal axis. The first and last four points from the photodetector were used for two linear fits. The back rise is the slope from fitting the first four points multiplied by the half length of the crystal. The δ_F is the slope per crystal radiation length from fitting the last four points. An early GEANT simulation concluded that the δ_F of crystal is required to be small for the best energy resolution and the back rise of crystal should be negative to compensate shower leakage [13]. While the BGRI sample shows the best LRU, the SIC sample shows a relatively lower light output and worse LRU compared to samples from BGRI and Incrom. It is due to the fact that the SIC sample is 5 cm longer than the others.

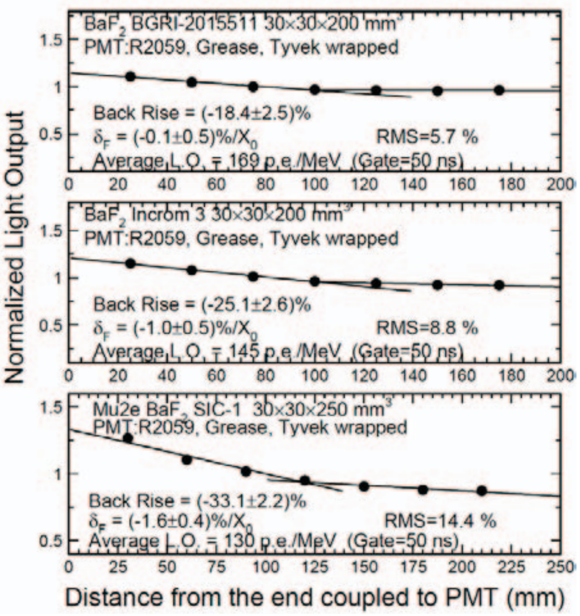

Fig. 3 Light output is shown as a function of the distance to the photodetector for large size BaF_2 crystals from three vendors.

Fig. 4 shows normalized EWLT (top) and light output (bottom) of the fast component as a function of the integrated dose for three BaF_2 crystals from different vendors. Both EWLT and LO values are 40% after 120 Mrad for these samples from thee different vendors, indicating that commercially available large size pure BaF_2 crystals have excellent radiation hardness against high ionization dose. It is also interesting to note that the radiation hardness of the sample SIC2012 is consistent with BaF_2 crystals batch produced twenty years ago [7, 14]. Our investigations also show that neutron induced damage in BaF_2 crystals is negligible as compared to ionization dose.

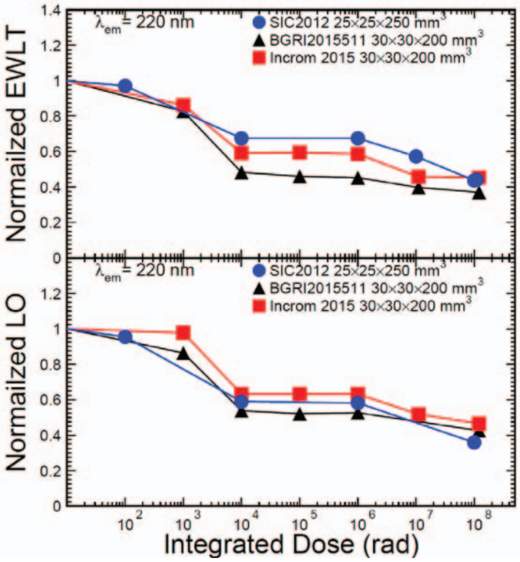

Fig. 4 Normalized EWLT and LO of the fast scintillation component are shown as a function of integrated dose for BaF_2 crystals from three vendors.

III. RARE EARTH DOPED BaF_2 CRYSTAL

Early works pointed out that doping BaF_2 crystals with rare earth would suppress the slow scintillation component [12]. Ten 3×3×2 cm^3 samples were cut from a BaF_2 ingot co-doped with La and Ce which was grown at BGRI. While the sample P1 was cut from the seed end, P10 is at the tail end. Fig.5 shows transmittance spectra measured for these La/Ce co-doped samples along the 3 cm path length. All transmittance between 400 and 800 nm approach the theoretical limit (black dots), indicating good optical quality.

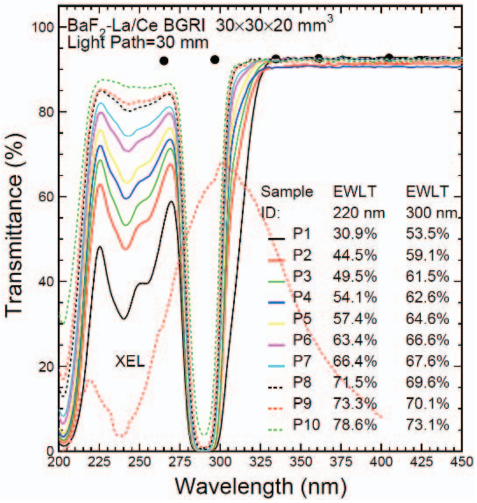

Fig.5 The transmittance of ten La/Ce co-doped BaF_2 crystal samples cut from the same ingot.

Two absorption bands are observed around 203 and 290 nm. While the absorption band around 290 nm is attributed to the Ce doping, that at 203 nm is suspected to be caused by the La doping. The 290 nm absorption band reduces the slow component and improves the overall F/S ratio. The intensities of both absorption bands weakened from the seed to the tail, indicating large segregation coefficients of La and Ce in BaF_2.

Fig. 6 shows the photoluminescence (PL) spectra of the La/Ce co-doped BaF_2 sample P1 with an excitation peak at 285 nm and two emission peaks at 305 and 325 nm, which are consistent with the Ce luminescence.

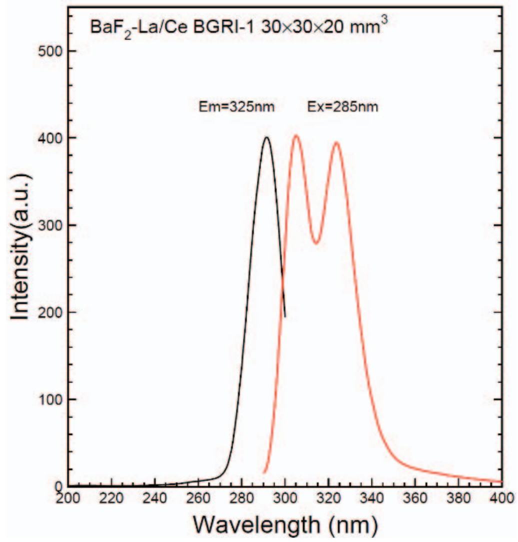

Fig. 6 Photoluminescence of BGRI La/Ce co-doped BaF_2 crystal

Fig.7 shows the decay time of 25 ns measured for PL at 324 nm with 291 nm excitation for the BaF_2 sample P1, which is also consistent with the Ce luminescence.

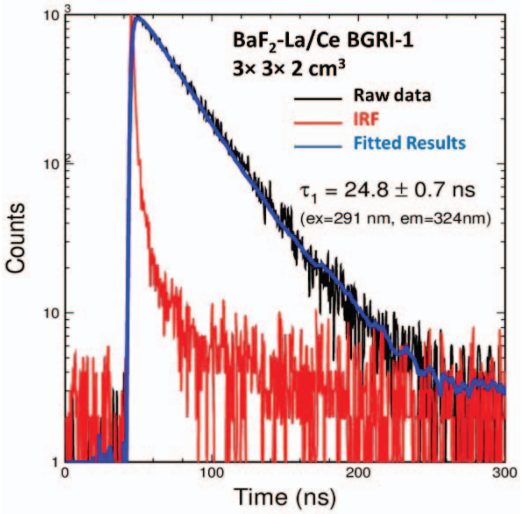

Fig. 7 The decay kinetics of PL of La/Ce co-doped BaF_2 sample P1

Fig.8 shows the decay kinetics of pure and four La/Ce co-doped BaF_2 samples excited by γ-rays. To accommodate the Ce luminescence with 25 ns decay time, the data were fitted to three time constants. Comparing to pure BaF_2, significant reduction is observed in both the light output and decay time of the slow component in these doped BaF_2 samples, which improves the F/S ratio. We also notice that the light output of the 25 ns decay component decreases significantly from the seed to the tail, confirming the large segregation coefficient of Ce in BaF_2.

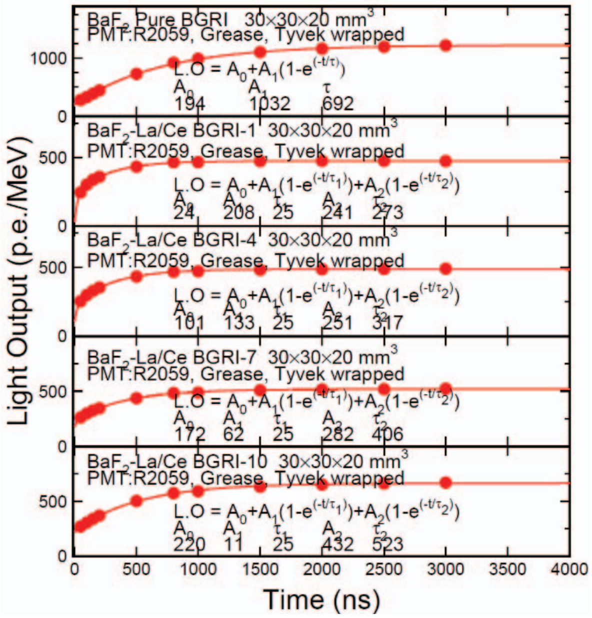

Fig.8 Light output is shown as a function of integration time for pure and La/Ce co-doped BaF_2 samples excited by γ-rays.

The top plot of Fig. 9 shows the light output in 50 ns (black dots) and 2500 ns (red squares) integration gates for ten La/Ce co-doped BaF_2 samples (top). Both light output in 50 and 2500 ns increases from the seed to the tail because of the large segregation of La and Ce in BaF_2. The bottom plot of Fig. 9 shows the corresponding ratio between the light output of 50 and 2500 ns gates with the maximum ratio of more than 50% in the samples near the seed end. Compared to the pure BaF_2, significant improvement in the F/S ratio is achieved by La/Ce co-doping. R&D will continue to optimize RE choice and doping level in BaF_2 for future HEP experiments at the intensity frontiers.

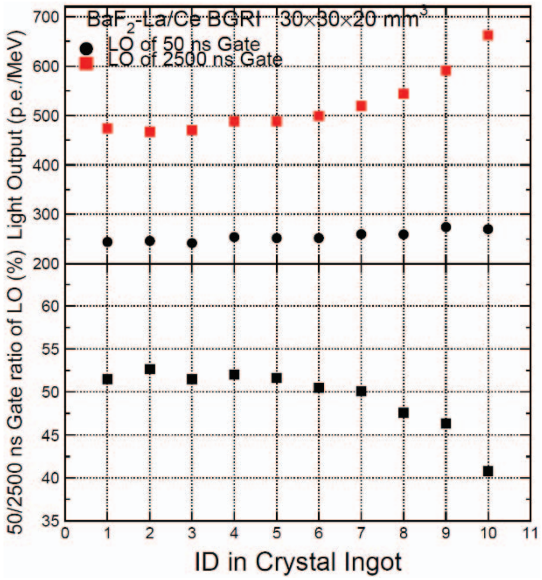

Fig.9 Light output in 50 and 2500 ns gate (top) and the corresponding ratio between 50 and 2500 ns gate for ten La/Ce co-doped BaF_2 samples

In addition to the ten small BaF_2 samples discussed above, a large La/Ce co-doped BaF_2 crystal of 3×3×20 cm^3 was also grown by BGRI. Fig 10 shows its longitudinal transmittance spectrum, indicating good optical quality and two absorption bands caused by Ce and La doping.

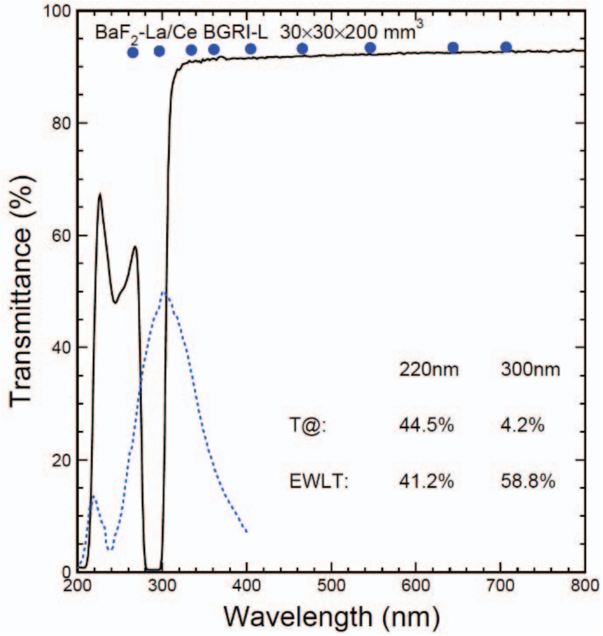

Fig. 10 Longitudinal transmittance of a 20 cm long BaF_2 crystal co-doped with La and Ce.

Fig 11 shows light output of 50 ns gate as a function of distance to the photodetector for this 20 cm long La/Ce co-doped BaF_2 crystal with the seed (top) and tail (bottom) end coupled to the PMT. This 20 cm long doped BaF_2 crystal has similar light response uniformity as compared to the pure BaF_2 crystal shown in Fig. 3, indicating that the doping approach is very promising for future HEP applications.

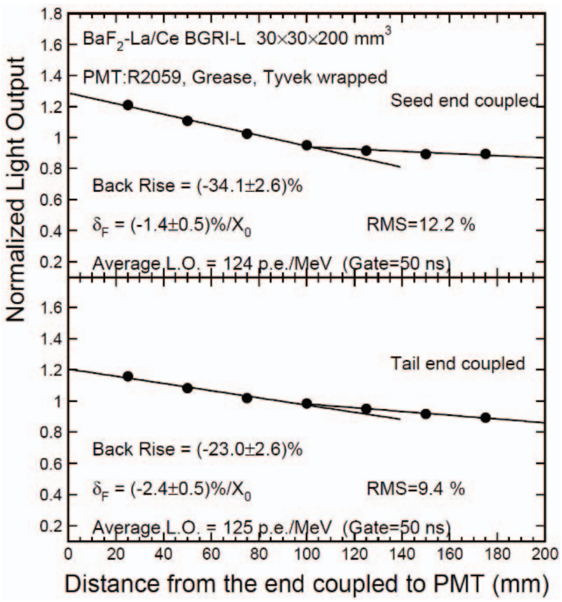

Fig.11 Light output is shown as a function of the distance to the photodetector for a 20 cm long La/Ce co-doped BaF_2 crystal.

IV. SUMMARY

The fast scintillation light with sub-ns decay time in BaF_2 crystals provides sufficient light output and excellent radiation hardness up to 120 Mrad. They promise a very fast and stable calorimeter in a severe radiation environment. The issue of BaF_2 crystal's slow scintillation light with 600 ns decay time can be handled by several approaches: selective readout with novel photo-detectors and selective RE doping in crystals.

The La/Ce co-doping in BaF_2 crystals were investigated. The 1st 20 cm long sample with La/Ce co-doping shows the overall 50/2500 ns LO ratio increased from 1:5 to 1:2 with adequate light response uniformity. Their radiation hardness, however, need further investigation.

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