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Performances of Crystal Scintillators in a Severe Radiation Environment Caused by Gamma Rays

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Performances of Crystal Scintillators in a Severe Radiation Environment Caused by Gamma Rays

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Abstract. Because of their superb energy resolution and detection efficiency crystal scintillators are widely used in high energy and nuclear physics experiments. A crucial issue is radiation damage. We report an investigation on γ-ray induced radiation damage in crystal scintillators of large size, including BaF_2, BGO, CeF_3, pure CsI, LSO/LYSO/LFS and PWO with an integrated dose up to 340 Mrad at a dose rate up to 1 Mrad/h. Optical and scintillation properties of these crystal samples were measured before and after irradiations. The result shows that pure CsI crystals have good radiation hardness below 100 krad. BaF_2, BGO and LYSO crystals show good radiation hardness beyond 1 Mrad. In terms of light output degradation LSO/LYSO/LFS is clearly the best among all scintillation crystals.

1. Introduction

Because of their superb energy resolution and detection efficiency, crystal scintillators are widely used in HEP experiments. The CMS lead tungstate ($PbWO_4$ or PWO) crystal calorimeter, for example, has played an important role in the discovery of the Higgs boson [1]. One crucial issue, however, is their radiation damage in a severe radiation environment, which requires precision monitoring to correct variations in crystal's transparency [2]. We report an investigation on ɣ-ray induced radiation damage in various crystal scintillators of more than 20 cm length, such as BaF_2 (20×20×250 mm^3), BGO (25×25×200 mm^3), CeF_3 (33×32×191 mm^3), pure CsI (50×50×300 mm^3), LYSO (25×25×200 mm^3) and PWO (28.5^2×30^2×220 mm^3). The 30 cm long pure CsI sample was irradiated to 1 Mrad, and was cut to 20 cm for irradiations beyond 1 Mrad. Gamma-ray irradiations up to 1 Mrad were carried out at two facilities at Caltech: an open ^{60}Co source and a sealed ^{137}Cs source. The former provides dose rates between 2 and 100 rad/h by placing samples at appropriate distances. The later provides a dose rate of about 7 krad/h in 2015 with 5% uniformity along the sample's longitudinal axis when the samples are placed at the center of the irradiation chamber [3]. Gamma-ray irradiations beyond 1 Mrad were carried out at the Total Ionization Dose (TID) facility of Jet Propulsion Laboratory (JPL), where a group of high intensity ^{60}Co sources provides an adjustable dose rate up to 1 Mrad/h in an opening throat of 10×10×13.5 inch. The irradiation at the TID facility was carried out in steps: 9, 90 and several steps of 100 Mrad each to reach 340 Mrad. The dose rate was 180 krad/h for the 9 Mrad irradiation and 1 Mrad/h for the rest.

2. LSO/LYSO/LFS Crystals

LYSO, LSO and LFS crystals by six different vendors are investigated. Figure 1 shows normalized emission weighted longitudinal transmittsnce (EWLT, top) and light output (LO, bottom) as a function of the integrated dose for six LYSO/LSO/LFS samples. EWLT is defined as [4]:

$$EWLT = \frac{\int LT(\lambda)Em(\lambda)d\lambda}{\int Em(\lambda)d\lambda} \quad (1)$$

The losses of EWLT and LO are about 35% and 42% respectively in OET LFS after 340 Mrad. The average LO loss after 10 Mrad is about 18% with a divergence of less than 7.5%, indicating good consistency of radiation hardness for crystals of this type from six vendors.

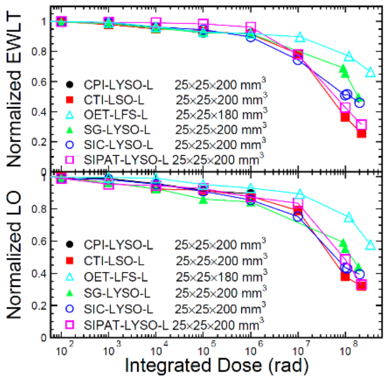

Figure 1. Normalized EWLT and LO are shown as a function of integrated dose up to 340 Mrad for six LYSO/LSO/LFS crystals from different vendors.

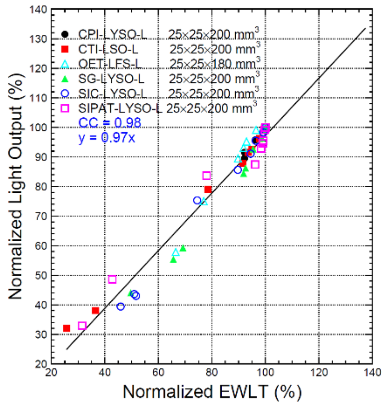

Figure 2. Correlation between normalized EWLT and LO is shown for six LYSO/LSO/LFS crystals from different vendors.

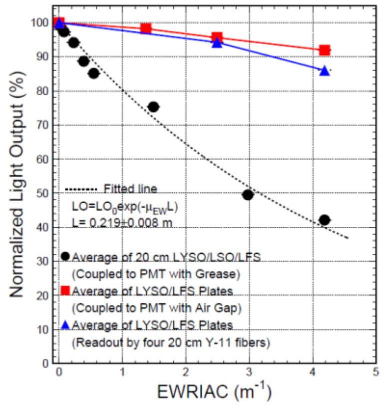

Figure 3. Normalized LO as a function of EWRIAC is shown for 20 cm long LYSO/LSO/LFS crystals and LYSO/LFS plates of 14×14×1.5 mm^3.

Figure 2 shows correlation between normalized EWLT and LO for six LYSO/LSO/LFS crystals. Also shown in the plot is a linear fit and the linear correlation coefficients (CC), defined as [5]:

$$\mathrm{CC} = \frac{\sum(x-\bar{x})(y-\bar{y})}{\sqrt{\sum(x-\bar{x})^2\sum(y-\bar{y})^2}} \qquad (2)$$

An excellent positive correlation of 97% is observed between normalized EWLT and LO for six LYSO/LSO/LFS crystals from different vendors, indicating that LO loss in crystals of this type is caused by transmittance loss, so may be corrected by using a light pulse based monitoring system.
Figure 3 shows normalized LO as a function of emission weighted radiation induced absorption coefficient (EWRIAC) for 20 cm long LYSO/LSO/LFS crystal samples as well as 14×14×1.5 mm^3 LYSO/LFS plates with five holes designed for the proposed LYSO/W Shashlik calorimeter [6]. While the LO of 20 cm long crystals (black dots) was measured by a PMT coupled to the samples directly, the LO of plates was measured by two methods. One is with the plates coupled to a PMT directly (red squares). The other is with the plate coupled a PMT through four Y-11 wavelength shift fibers (blue triangles). After 100 Mrad irradiation, the LYSO/LSO/LFS samples have a EWRIAC value of 3 m^{-1}. The corresponding measured LO loss is about 50% for 20 cm long crystals, and 4% and 6% respectively for the 14×14×1.5 mm^3 plates directly coupled to the PMT and through Y-11 WLS fibers. Compared to 20 cm long crystals, about a ten times better radiation hardness is observed by reducing the light path length in 14×14×1.5 mm^3 plates, which greatly enhances the radiation hardness of the LYSO/W Shashlik calorimeter as compared to a LYSO calorimeter of total absorption. An exponential fit reveals that the average scintillation light path length in 20 cm long crystals is about 22 cm. The data shown in Figure 3 may be used to estimate performance of LYSO/LSO/LFS crystals under γ-ray irradiation.

3. BaF_2, CeF_3, CsI, BGO and PWO crystals

It is well known that γ-ray induced radiation damage in BaF_2 and pure CsI crystals does not recover at room temperature [7, 8], so is dose rate independent. Figure 4 shows normalized EWLT (top) and LO (bottom) of the fast scintillation component as a function of integrated dose for three BaF_2 crystals from different vendors, where the fast component refers to scintillation light peaked at 220 nm with scintillation decay time of less than 1 ns. While the sample SIC2012 was grown at SICCAS in 2012, the samples BGRI 2015 and Incrom 2015 were grown at BGRI and Incrom respectively in 2015. Figure 5 shows the normalized EWLT (top) and LO (bottom) as a function of the integrated dose for two pure CsI crystal samples from different vendors. The 30 cm long samples SIC2013 was grown at SICCAS in 2013. The 23 cm long sample Kharkov 1 was grown at Kharkov in 2015. The sample SIC2013 was 30 cm long when it was irradiated up to 1 Mrad, and was cut to 20 cm for irradiations beyond 1 Mrad at the TID facility of JPL. The samples from SICCAS and Kharkov show consistent radiation hardness. The LO is about 80% after 100 krad, and was reduced to about 30% after 1 Mrad, indicating that pure CsI is radiation hard at low doses up to 100 krad but not beyond. It is also noticed that the radiation hardness of sample SIC 2013 is consistent with the sample Kharkov 2015 and two Kharkov samples grown twenty years ago [8].

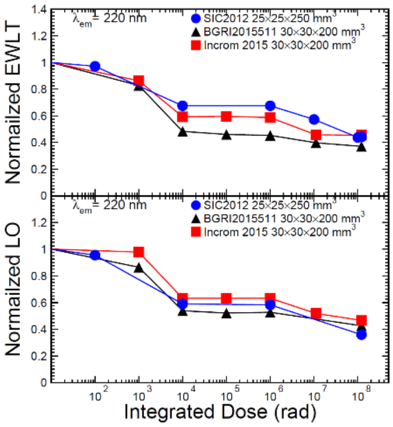

Figure 4. Normalized EWLT and LO of the fast scintillation component as a function of integrated dose for three BaF_2 crystals from different vendors.

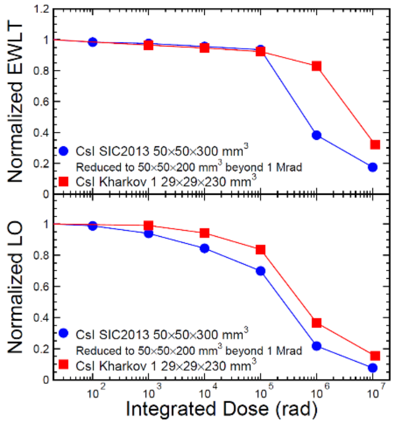

Figure 5. Normalized EWLT and LO are shown as a function of integrated dose for two pure CsI crystals from different vendors.

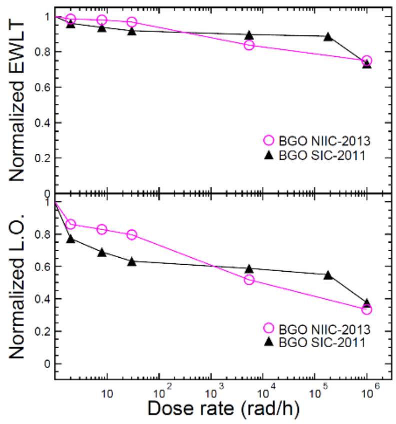

Figure 6. Normalized EWLT (top) and LO (bottom) are shown as a function of dose rate for two BGO crystals from different vendors.

Radiation damage in BGO, CeF_3 and PWO crystals recovers under room temperature, leading to a dose rate dependent damage [9, 10]. Figure 6 shows the normalized EWLT (top) and LO (bottom) in equilibrium as a function of the dose rates for two BGO crystal samples from different vendors. The radiation hardness of these two samples from different vendors is more or less consistent. Early BGO crystals produced for the L3 experiment, however, are not as radiation hard as these samples [10], indicating that crystal quality is improved during mass production for the medical industry.

Figure 7 shows the normalized EWLT (top) and LO (bottom) in equilibrium as a function of the dose rates for two CeF_3 crystal samples. Consistent radiation hardness was observed in these samples. The LO of CeF_3 crystal SIC2014 was too low to be measured under the 1 Mrad/h irradiation. Both samples were grown twenty year ago. Development is required to improve radiation hardness of CeF_3 for this material to be used in a severe radiation environment.

Figure 8 shows the normalized EWLT (top) and LO (bottom) in equilibrium as a function of the dose rates for two PWO-II crystals recently grown by BTCP for Panda and one PWO crystal recently grown by SICCAS for JLAB. Also shown in the plot is a PWO crystal grown about fifteen years ago by SIC for CMS. Previous investigations show that the radiation hardness of PWO crystals against ionization dose is diverse, and has no correlation with their initial optical quality [5]. Although selected samples grown recently are better than that grown for CMS about 15 years ago, quality control is still required to make sure PWO crystals used to construct future calorimeter meet a well-defined specification for crystal’s radiation hardness.

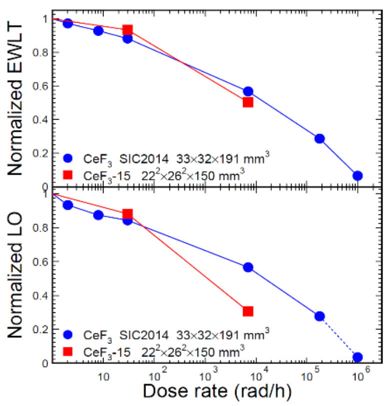

Figure 7. Normalized EWLT (top) and LO (bottom) are shown as a function of dose rate for two CeF_3 crystals

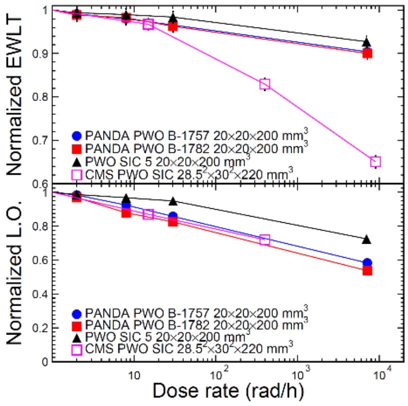

Figure 8. Normalized EWLT (top) and LO (bottom) are shown as a function of dose rate for four PWO crystal samples

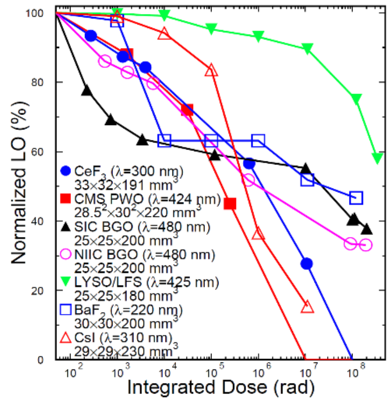

Figure 9. Normalized LO as a function of integrated dose for various crystals

4. Summary

In this investigation no recovery was observed after 200 Mrad irradiation in two LYSO samples, indicating radiation damage in LYSO is not dose rate dependent. Consistent degradation in transmittance and light output was observed for 20 cm long LYSO/LSO/LFS crystals from six vendors, indicating that radiation damage in commercially produced crystals of this type is under control. Because of its high cost due to expensive raw materials and high melting point, however, future crystal calorimeters may consider alternative cost-effective crystals.

Ionization induced radiation damage in LSO/LYSO/LFS, BaF_2 and pure CsI does not recover under room temperature. That in BGO, CeF3 and PWO does, leading to a dose rate dependent damage. A dose rate dependent damage level requires frequent monitoring and thus detector cost.

Ignoring the dose rate dependence, Figure 9 shows the normalized LO as a function of integrated dose for various long crystal samples. In terms of light output loss, LYSO clearly shows the best radiation hardness among all crystal scintillators. The best sample of this type maintains 75% and 60% LO after 100 and 340 Mrad. On the other hand, BGO and BaF_2 crystals also maintain 35% and 45% LO respectively after 200 and 120 Mrad, so may be considered as cost-effective alternatives for future HEP experiments with severe radiation environment. Pure CsI shows good radiation hardness below 100 krad. Because of its low cost, it is a good alternative for future HEP experiments in a modest radiation environment.

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References

[1] S. Chatrchyan, V. Khachatryan, A. M. Sirunyan, A. Tumasyan, W. Adam, E. Aguilo, *et al.* 2012 *Physics Letters B* **716** 30
[2] R. Y. Zhu 2004 *IEEE T Nucl Sci* **51** 1560
[3] J. M. Chen, R. H. Mao, L. Y. Zhang, and R. Y. Zhu 2007 IEEE T Nucl Sci **54** 1319
[4] J. M. Chen, R. H. Mao, L. Y. Zhang, and R. Y. Zhu 2007 *IEEE T Nucl Sci* **54** 718
[5] J. M. Chen, R. H. Mao, L. Y. Zhang, and R. Y. Zhu 2007 *IEEE T Nucl Sci* **54** 375
[6] L. Y. Zhang, R. H. Mao, F. Yang, and R. Y. Zhu 2014 *IEEE T Nucl Sci* **61** 483
[7] R. Y. Zhu 1994 *Nucl Instrum Meth A* **340** 442
[8] Z. Y. Wei and R. Y. Zhu 1993 *Nucl Instrum Meth A* **326** 508
[9] R. Y. Zhu 1998 *Nucl Instrum Meth A* **413** 297
[10] F. Yang, R. H. Mao, L. Y. Zhang, and R. Y. Zhu 2012 *J. Phys.: Conf. Ser* **404** 012025