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A Study of the Impact of Radiation Exposure on Uniformity of Large CsI(Tl) Crystals for the BaBar Detector

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Abstract

We describe an apparatus that allows simultaneous exposure of large CsI(Tl) crystals to radiation and precise measurement of the longitudinal changes in light yield of the crystals. We present herein the results from this device for exposures up to 10 kRad.

1 Introduction

The BaBar electromagnetic calorimeter (EMC) [1] consists of 6580 CsI(Tl) crystals ranging between 16 and 17.5 radiation lengths in depth. The radiation length of CsI(Tl) is 1.85 cm. The crystals are pyramids with a trapezoidal cross-section typically $4.7 \times 4.7\,\mathrm{cm}^2$ at the front and $6.0 \times 6.0\,\mathrm{cm}^2$ at the back.

The scintillation light collection efficiency is not necessarily constant along the length of the crystal. This non-uniformity may result from variations in crystal clarity, surface finish and wrapping. The EMC crystals were wrapped with two layers of diffuse white reflector, each 165 μm thick. The uniformity of light output along the wrapped crystal was measured by recording the signal from a highly collimated radioactive source at 20 points along the length of the crystal. The target for the non-uniformity contribution to the resolution of the EMC was less than 0.5%. It led to the requirement for the light yield (LY) to be uniform within $\pm 2\%$ in the front 10 cm of the crystal, the limit increasing linearly up to maximum of $\pm 5\%$ at the rear face (see Figure 2(a)). Adjustments were made on individual crystals to meet these criteria by selectively roughing or polishing the crystal surface to reduce or increase reflectivity [2].

The total exposure of the crystals in EMC is expected to reach up to 10 kRad

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Fig. 1. Experimental Setup: crystal array on the left, ^{60}Co source on the right.

during the 10 year lifetime of the experiment. This radiation dose is caused primarily by low energy (up to 10 MeV) photons. These photons deposit nearly all of their energy in the front third of the crystal. The resulting crystal damage may affect the uniformity of the light output along the length of the crystal. Previous studies [3] of the change in the longitudinal response by irradiation were inconclusive. To understand the impact of the radiation exposure on the degradation of the EMC energy resolution we have constructed an apparatus that allows precise measurement of the longitudinal changes in light yield of large CsI(Tl) crystals. The systematic errors in these measurements are minimized by performing all the longitudinal scans completely in-situ, interleaved with Co^{60} exposures.

2 Experimental Setup

The apparatus is shown in Figure 1. An assembly consists of 2×8 crystals [4] produced from a melt of CsI salt doped with 0.1 % thallium, using either Kyropoulos (Type A) or Bridgman (Type B) growth techniques. The crystals are read out with Hamamatsu R2154-06 photomultiplier tubes (PMT). Four stepper motors move two Pb collimators with ^{88}Y sources in vertical and horizontal planes. The assembly is irradiated uniformly (maximum dose variations are less than 15%) from the front face at a rate of $1-2$ Rad/hour by photons from a ^{60}Co source located 1 m from the assembly. The long outside surface of the crystals is shielded by a 5 cm steel plate with 0.91 cm holes drilled every 2 cm along each crystal length for collimation. The low dose rate and geometrical configuration were chosen to approximate radiation exposure of the crystals in the BaBar electromagnetic calorimeter, under typical beam conditions.

A small CsI(Tl) crystal with PMT and ^{88}Y, ^{22}Na and ^{228}Th sources, located

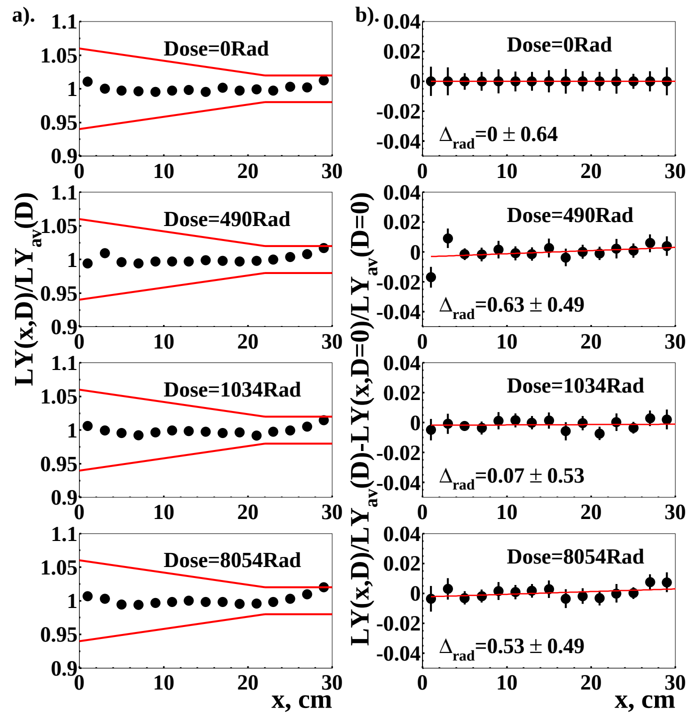

Fig. 2. a. Typical uniformity scan results for Type A crystal, solid line corresponds to the crystal uniformity requirement; b. Irradiation contribution to the uniformity, solid line corresponds to the fit results. Note: x=0 is the back of the crystal.

behind 10 cm of lead, is used as a standard reference to compensate for the drift of electronics. We use ten AD592s [5] for the temperature monitoring. The day-night temperature difference in the experimental room was less than 2° C. A light pulser system with light fibers connected to the face of each crystal is used to monitor the electronics. Radiation monitoring is done with two GM tubes with a computer readout for the current dose monitoring and thermo-luminescent dosimeters for the total dose monitoring. Data is read out through the CAMAC crate/SCSI card to a PC.

3 Measurements

Thirty five irradiations were made increasing the exposure incrementally between each. The total dose currently is 10 kRad. After waiting 6 hours between exposures, data points were taken in 2 cm steps along the length of each crystal.

The results of longitudinal scans at a selection of doses are presented for typical crystals of Type A and B in Figure 2(a) and 3(a) respectively.

As we are interested only in the dose dependent contribution to the non-

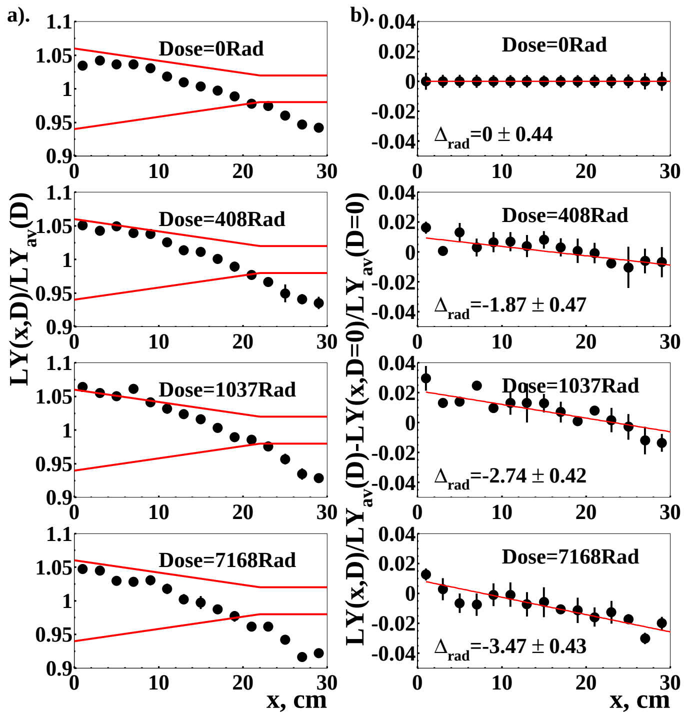

Fig. 3. a. Typical uniformity scan results for Type B crystal, solid line corresponds to the crystal uniformity requirement; b. Irradiation contribution to the uniformity, solid line corresponds to the fit results. Note: x=0 is the back of the crystal.

uniformity (Figure 2(b) and 3(b)) we can parametrize it as a linear function of position along the length of the crystal (x):

$$\frac{LY(x,D)}{LY_{av}(D)} - \frac{LY(x,D=0)}{LY_{av}(D=0)} = \frac{\Delta_{rad}(D)}{T}\left(\frac{T}{2} - x\right), \tag{1}$$

where $\Delta_{rad}(D)$ is a percentage drop in the light yield from the back to the front of the crystal caused by irradiation, LY_{av} is the light output averaged over all positions along the crystal length, T is the length of the crystal, x is the position along the crystal length and D is the dose.

The dose dependence of $\Delta_{rad}(D)$ is shown in Figure 4. It can be parametrized as follows:

$$\Delta_{rad}(D) = a \cdot log_{10}^2 D + b \cdot log_{10} D + c. \tag{2}$$

The crystals can be organized into three categories:

- $b < -1$: two crystals of Type A and three crystals of Type B (B1)
- $b > -1$: three crystals of Type B (B2)
- $|a| > 0$: two crystals of Type B (B3)

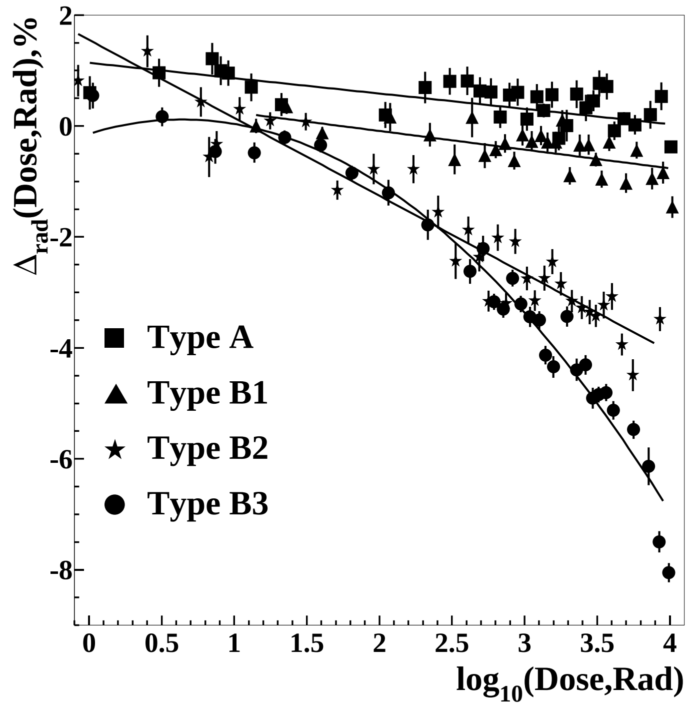

Fig. 4. Dose dependence of the percentage drop of the light yield for a sample of different crystal types.

Table 1
Parametrization of the $\Delta(D)$ in percent

	a	**b**	**c**
Type A	-	-0.29±0.06	0.88±0.17
Type B1	-	-0.43±0.06	0.48±0.17
Type B2	-	-1.39±0.06	1.61±0.18
Type B3	-0.68±0.05	1.24±0.22	-0.38±0.23
Type B	-	-1.23±0.03	1.43±0.09

Averaging the fits for 2 Type A and 8 Type B crystals we obtain values of a, b and c for each of the types (see Table 1). Using linear fit results only we estimate a light yield percentage drop at 10 kRad of $\Delta^{A}_{rad}(10\,\mathrm{kRad}) = (-0.3 \pm 0.3)\%$ for Type A crystals and of $\Delta^{B}_{rad}(10\,\mathrm{kRad}) = (-3.5 \pm 0.2)\%$ for Type B crystals. The measured average light yield percentage drop at 10 kRad is $(-0.4 \pm 0.5)\%$ and $(4.0 \pm 0.7)\%$ for crystals of Type A and Type B correspondingly, which is in good agreement with the estimates [6].

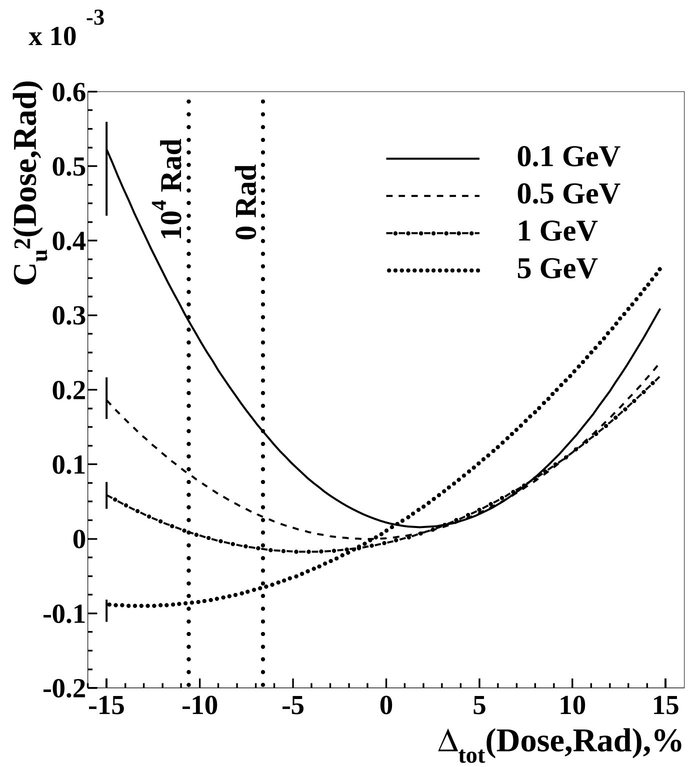

Fig. 5. MC study of the non-uniformity contribution to the energy resolution (C_u) dependence on the total drop of the light yield (Δ_{tot}). The error bars show typical uncertainties in the curves

4 Study of the impact of non-uniformity

The energy resolution of the BaBar calorimeter extracted from a variety of processes - radioactive source, symmetric π^0 and η decays, $\chi_{c1} \to J/\psi\gamma$, and Bhabha events - is [8]:

$$\frac{\sigma_E}{E} = \frac{(2.30 \pm 0.03 \pm 0.30)\%}{\sqrt[4]{E(GeV)}} \oplus (1.35 \pm 0.08 \pm 0.20)\% \tag{3}$$

The first term comes from fluctuations in photon statistics, electronic noise and beam backgrounds; it is dominant at low energies. The constant term arises from non-uniformity in light collection, front and rear shower leakage and uncertainties in calibration; it dominates at high energies.

We studied the effect of the light response uniformity on the energy resolution using full BaBar GEANT 4 simulation without beam backgrounds. Single photons of 100 MeV, 500 MeV, 1 GeV and 5 GeV were produced at $|cos\theta| < 0.2$. Each crystal was divided into eight longitudinal slices. The non-uniformity was simulated as weights on the energy deposited in each slice.

Table 2
Estimate of the EMC resolution for single photons in %

	$0.1\,\mathbf{GeV}$	$0.5\,\mathbf{GeV}$	$1\,\mathbf{GeV}$	$5\,\mathbf{GeV}$
$\frac{\sigma_E}{E}(0\,\mathbf{Rad})$	4.30±0.58	3.05±0.42	2.66±0.37	2.05±0.29
$C_u(0\,\mathbf{Rad})$	1.19	0.54	-0.37	-0.81
$C_u(10\,\mathbf{kRad})$	1.71	0.93	-0.30	-0.93
$\frac{\sigma_E}{E}(10\,\mathbf{kRad})$	**4.47**	**3.14**	**2.67**	**2.00**

The non-uniformity contribution to the energy resolution is shown in Figure 5. From the measured energy resolution (Eq.3) we obtain the energy resolution for single photons of different energies, $\frac{\sigma_E}{E}$ (Table 2, line 1). Knowing the percentage drop for the EMC crystals at zero dose to be $\Delta_0 = (-6.6 \pm 0.6)\%$ ([7]) one can estimate from Figure 5 the initial non-uniformity contribution to the energy resolution, C_u (Table 2, line 2). Assuming the maximum predicted non-uniformity increase for 10 kRad the total percentage drop in the light yield is $\Delta_{tot}(10\,\mathrm{kRad}) = \Delta_0 + \Delta^B_{rad}(10\,\mathrm{kRad}) = (-10.6 \pm 0.6)\%$. This allows us to estimate from Figure 5 the non-uniformity contribution to the energy resolution at 10 kRad, $C_u(10\,\mathrm{kRad})$ (Table 2, line 3). Note that negative values of C_u^2 mean that sometimes non-uniformity improves the energy resolution. This is the case for photons with energies of a few GeV for which high values of the light yield at the back of the crystal compensate rear shower leakage. From the considerations above, we predict the energy resolution at 10 kRad from the initial energy resolution by subtracting the non-uniformity contribution at zero dose and adding the non-uniformity contribution at 10 kRad in quadrature as follows:

$$\frac{\sigma_E}{E}(D) = \sqrt{\frac{\sigma_E^2}{E^2}(0) - (\pm C_u^2(0)) + (\pm C_u^2(D))}, \tag{4}$$

where D is 10 kRad and $\pm$ corresponds to the sign of C_u^2. Comparing line 1 and line 4 in Table 2, one can see that contribution of non-uniformity to the EMC resolution for doses up to 10 kRad is negligible.

5 Conclusion

In this study we measured the dose dependence of the drop in the light yield from the back to the front of the crystal to be $(-0.29 \pm 0.06) \cdot \log_{10} D + (0.88 \pm 0.17)\%$ for crystals grown by the Kyropoulos growth technique (Type A) and to be $(-1.23 \pm 0.04) \cdot \log_{10} D + (1.43 \pm 0.09)\%$ for crystals grown by the Bridgman growth technique (Type B). On the basis of this measurement we were able to develop a correction function (Eq. 1) to be used in Monte Carlo simulation to incorporate the effect of radiation damage to the crystal light yield uniformity. We estimate that even for the maximum observed uniformity decrease of 4% at 10 kRad, the EMC resolution will not be degraded significantly.

6 Acknowledgment

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7 Figure captions

Fig. 1: Experimental Setup: crystal array on the left, ^{60}Co source on the right.

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Fig. 4: Dose dependence of the percentage drop of the light yield for a sample of different crystal types.

Fig. 5: MC study of the non-uniformity contribution to the energy resolution (C_u) dependence on the total drop of the light yield (Δ_{tot}). The error bars show typical uncertainties in the curves.

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[4] Sixteen crystals studied in this experiment were part of the pool of "spares" which remained after the construction of the EMC. Out of those 16 crystals 4 Type A crystals were produced by Crismatec, Nemours, France and of Type B crystals 11 were made in Shanghai Institute of Ceramics, Shanghai, P.R. China and 1 in Beijing Glass Research Institute, Beijing, P.R. China. We have excluded 1 Shanghai and 1 Crismatec crystals from the current paper because of readout electronics problems. Another 2 Shanghai, 1 Crismatec and 1 Beijing crystals were excluded because we believe that they were not representative of the quality of the crystals installed in the EMC. Thus the results of this paper are based on 8 Shanghai and 2 Crismatec crystals.

[5] AD592 is a two terminal monolithic integrated circuit temperature transducer produced by Analog Devices, USA.

[6] Previously [7] we reported the value of $\Delta^B_{rad}(10\,\mathrm{kRad}) = (-3.0 \pm 0.2)\%$, which is 1% lower than measured after extending dose to 10 kRad. This can be explained by the existence of Type B3 crystals with non-linear dose dependence of $\Delta^B_{rad}(D)$ which has not been established at 6 kRad.

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