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A systematic study of radiation damage to large crystals of CsI(Tl) for the BaBar detector

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***Abstract*— We describe a novel 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 first results from this device for exposures up to 6 kRad.**

I. 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 total exposure of the crystals in EMC is expected to reach up to 10 kRad during the 10 year lifetime of the experiment. This integrated dose induces damage to the crystals, which may be exhibited in two ways: a drop in the light output and a change in the uniformity of the light output from energy deposition along the length of the crystal.

The energy resolution of the 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 [2]:

$$\frac{\sigma_E}{E} = \frac{(2.30 \pm 0.03 \pm 0.30)\%}{\sqrt[4]{E(GeV)}} \oplus (1.35 \pm 0.08 \pm 0.20)\% \quad (1)$$

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. Both terms are affected by radiation exposure.

A drop in the light output caused by radiation exposure will result in a decrease of the photon statistics. The initial average light output of crystals was measured to be 3900 photoelectrons/MeV using standard EMC readout [3]. For the projected exposure over the lifetime of the BaBar experiment (10 kRad) the light yield drop would be $30\,\%$ [4]. Thus its contribution towards degrading the energy resolution will be negligible compared to other contributions.

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 [5], each $165\,\mu$m 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. Adjustments were made on individual crystals to meet these criteria by selectively roughing or polishing the crystal surface to reduce or increase reflectivity [6].

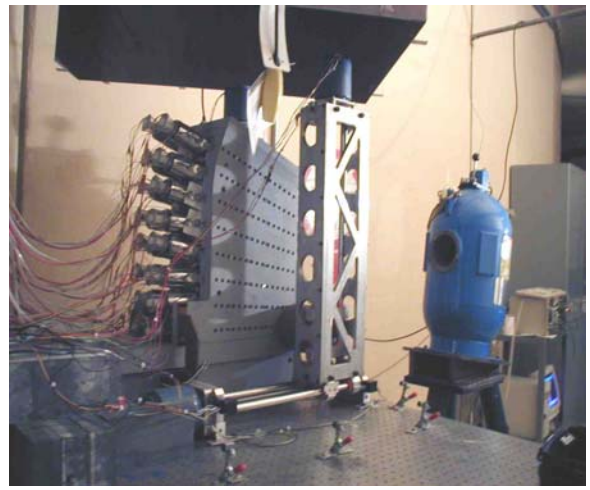

Fig. 1. Experimental Setup: crystal array on the left, ^{60}Co source on the right.

During the course of the BaBar experiment the EMC crystals accumulate a radiation dose caused primarily by low energy (up to 10 MeV) photons [7]. These photons deposit nearly all of their energy in the front third of the crystal, which may affect the uniformity of the light output along the length of the crystal. Previous studies [8] of the change in the longitudinal response by irradiation were inconclusive. To understand the impact of the radiation exposure 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.

II. Experimental Setup

The apparatus is shown in Figure 1. An assembly consists of 2×8 crystals [9] which are read out with Hamamatsu R2154-06 photomultiplier tubes (PMT). Four stepper motors move

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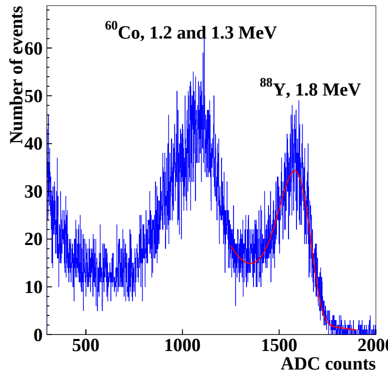

Fig. 2. Typical crystal spectrum and fit to the ^{88}Y line

two Pb collimators with ^{88}Y sources in vertical and horizontal planes. The assembly is irradiated uniformly 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 sides of the crystals are shielded by two 5 cm steel plates 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 imitate 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 behind 10 cm of lead, is used as a standard reference to compensate for the drift of electronics. We use 10 AD592s [10] 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 2 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 [11] crate/SCSI card to a PC.

III. Measurements

We used sixteen full-size CsI(Tl) crystals, produced from a melt of CsI salt doped with 0.1 % thallium, using either Kyropoulos (Crismatec [12]) or Bridgman (Shanghai [13]) growth techniques.

The exposures started at 1 Rad and were doubled between each longitudinal scan. The total dose currently is 5833 Rad. After waiting 6 hours between exposures, data points were taken in 2 cm increments along the length of each crystal. A typical energy spectrum after 5 minutes of data-taking is presented on Fig. 2. We used the Logarithmic Normal Distribution [15] to fit the signal peak region:

$$f_s(E) = N_s \cdot e^{\left[-\frac{1}{2\tau^2}\ln^2\left(1+\tau\cdot(E-\mu)\cdot\frac{\sinh(\tau\sqrt{\ln 4})}{\sigma\tau\sqrt{\ln 4}}\right)+\tau^2\right]}, \quad (2)$$

where N_s is signal normalization, μ the mean value, τ a parameter for the tail, σ is $\frac{FWHM}{2.36}$ and E is energy. An exponential function was used for the background parametrization.

The results of longitudinal scans at a selection of doses are presented for typical Shanghai and Crismatec crystals in Fig.3(a) and 4(a) respectively.

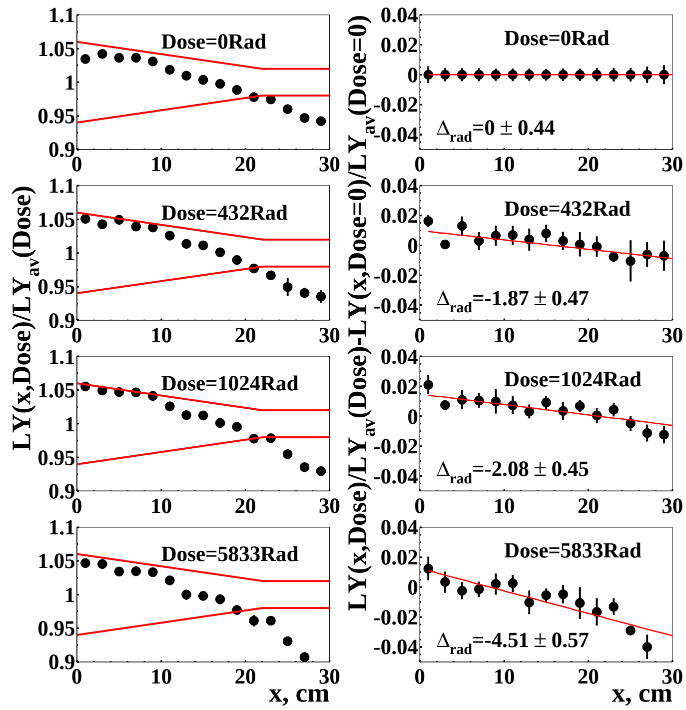

Fig. 3. a. Typical uniformity scan results (Shanghai), red line corresponds to the crystal uniformity requirement b. Irradiation contribution to the uniformity, red line corresponds to the fit results Note: x=0 is the back of the crystal

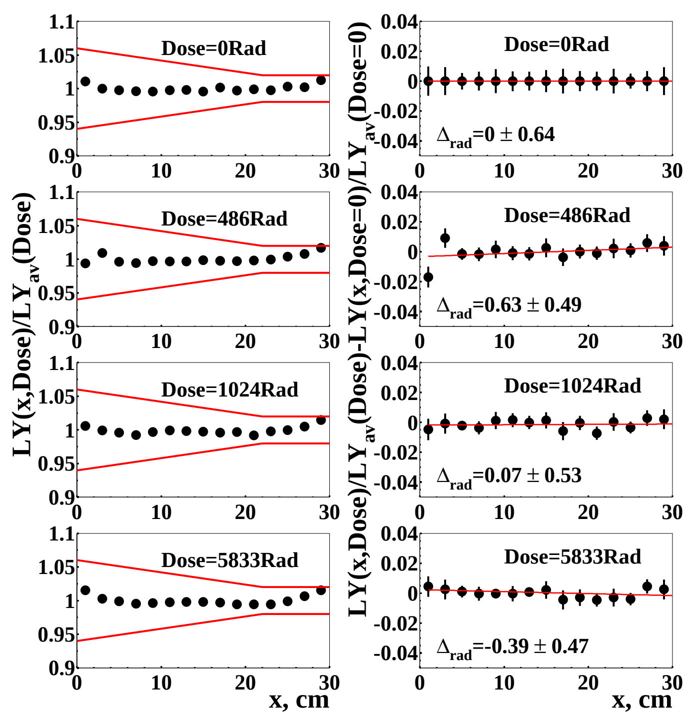

Fig. 4. a. Typical uniformity scan results (Crismatec) , red line corresponds to the crystal uniformity requirement b. Irradiation contribution to the uniformity, red line corresponds to the fit results Note: x=0 is the back of the crystal

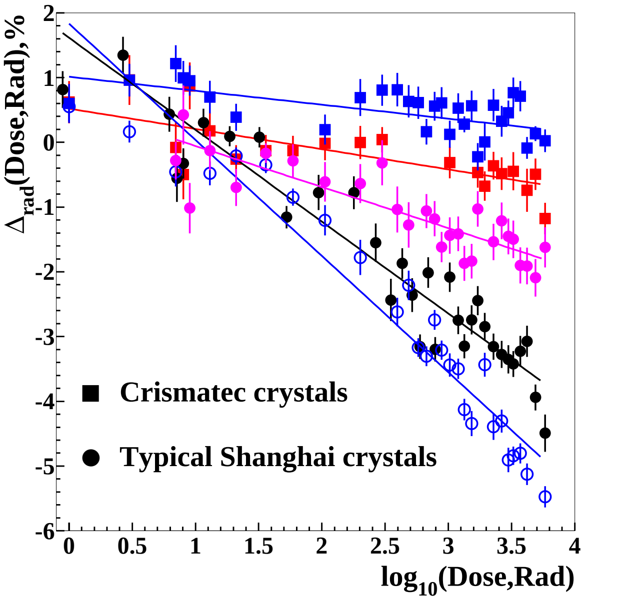

Fig. 5. Dose dependence of the percentage drop of the light yield for different crystals

TABLE I
PARAMETRIZATION OF THE $\Delta(D)$ IN PERCENT

	Crismatec	Shanghai
A	-0.25±0.06	-1.12±0.04
B	0.81±0.18	1.46±0.12

As we are interested only in the dose dependent contribution to the non-uniformity (Fig 3(b) and 4(b)) we can parametrize it as a linear function of position along the length of the crystal (x):

$$\frac{LY(x,D)}{LY_{av}(D)} - \frac{LY(x,D=0)}{LY_{av}(D=0)} = \frac{\Delta_{rad}(D)}{T}\left(\frac{T}{2} - x\right), \quad (3)$$

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 $\Delta_{rad}(D)$ as shown in Figure 5 is not discernible up to approximately 10 Rad. For doses above that it can be parametrized as follows:

$$\Delta_{rad}(D) = A \cdot log_{10}D + B. \quad (4)$$

Averaging the fits for 2 Crismatec and 8 Shanghai crystals we obtain values of A and B for each of the manufacturers (see Table I). Using Eq.4 we estimate a light yield percentage drop at 10 kRad of $\Delta^{Cr}_{rad}(10^4\,\text{Rad}) = (-0.2 \pm 0.3)\%$ for Crismatec crystals and of $\Delta^{Sh}_{rad}(10^4\,\text{Rad}) = (-3.0 \pm 0.2)\%$ for Shanghai crystals.

IV. Study of the Impact of Non-Uniformity

The effect of the light response uniformity on the energy resolution has been studied 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.

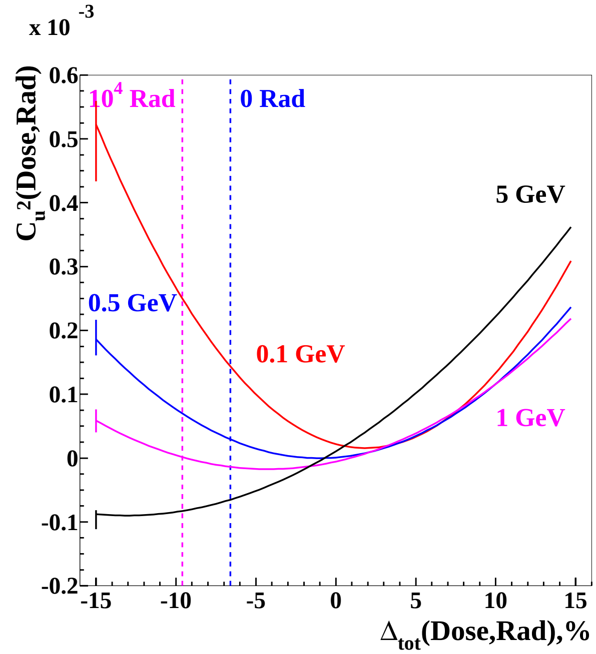

Fig. 6. MC study of the non-uniformity contribution to the energy resolution (C_u) dependence on the total drop of the light yield (Δ_{tot}). The error bars show typical uncertainties in the curves

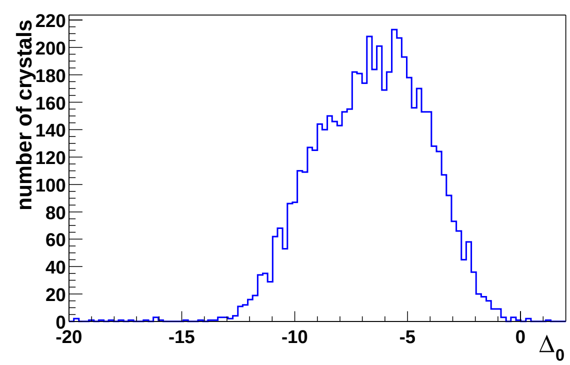

Fig. 7. Distribution of the initial drop in the light yield (Δ_0) of 5760 EMC barrel crystals (all manufacturers)

The non-uniformity contribution to the energy resolution is shown in the Figure 6. From the measured energy resolution (Eq.1) we obtain the energy resolution for single photons of different energies, $\frac{\sigma_E}{E}$ (Table II, line 1). Knowing the percentage drop for the EMC crystals at zero dose to be $\Delta_0 = (-6.6 \pm 0.6)\%$ (see Figure 7), one can estimate from Figure 6 the initial non-uniformity contribution to the energy resolution, C_u (Table II, line 2). Assuming the maximum predicted non-uniformity increase for 10 kRad the total percentage drop in the light yield is $\Delta_{tot}(10^4\,\text{Rad}) = \Delta_0 + \Delta^{Sh}_{rad}(10^4\,\text{Rad}) =$

TABLE II

ESTIMATE OF THE EMC RESOLUTION FOR SINGLE PHOTONS IN %

	0.1 **GeV**	0.5 **GeV**	1 **GeV**	5 **GeV**
$\frac{\sigma_E}{E}(0\,\textbf{Rad})$	4.30±0.58	3.05±0.42	2.66±0.37	2.05±0.29
$C_u(0\,\textbf{Rad})$	1.19	0.54	-0.37	-0.81
$C_u(10^4\,\textbf{Rad})$	1.58	0.84	-0.12	-0.91
$\frac{\sigma_E}{E}(10^4\,\textbf{Rad})$	**4.42**	**3.11**	**2.68**	**2.01**

$(-9.6 \pm 0.6)\%$. This allows us to estimate from Figure 6 the non-uniformity contribution to the energy resolution at $10\,$kRad, $C_u(10^4\,\text{Rad})$ (Table II, 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:

$$\frac{\sigma_E}{E}(D) = \sqrt{\frac{\sigma_E^2}{E^2}(0) - (\pm C_u^2(0)) + (\pm C_u^2(D))}, \qquad (5)$$

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

V. 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 $(-0.25 \pm 0.06) \cdot \log_{10} D + (0.81 \pm 0.18)\%$ for crystals grown by the Kyropoulos growth technique (Crismatec) and to be $(-1.12 \pm 0.04) \cdot \log_{10} D + (1.46 \pm 0.12)\%$ for crystals grown by the Bridgman growth technique (Shanghai). On the basis of this measurement we were able to develop a correction function (Eq. 3) 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 3% at $10\,$kRad, the EMC resolution will not be degraded significantly.

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[9] 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 11 were Shanghai [13], 4 Crismatec [12] and 1 Beijing [14] crystal. 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.

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

[11] Jorway 73A CAMAC crate controller and CAMAC controller software (Fermitools).

[12] Crismatec, Nemours, France.

[13] Shanghai Institute of Ceramics, Shanghai, P.R. China.

[14] Beijing Glass Research Institute, Beijing, P.R. China; grown by Bridgman growth method.

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