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Study of Possible Scintillation Mechanism Damage in PbWO₄ Crystals After Pion Irradiation

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Abstract

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We employed two independent methods to study possible damage to the scintillation mechanism in lead tungstate crystals due to irradiation by a 34 GeV pion beam. First, 10 crystals were irradiated simultaneously over 30 hours by a narrow beam, so that only a small region of each crystal was affected. We studied the effect of the irradiation on the light output non-uniformity. If a localized degradation was observed, it would indicate damage to the scintillation mechanism. Secondly, we detected light output using two phototubes attached to sides of a crystal. Since these phototubes detect scintillation light only from a small localized region, the effect of transmission loss should be minimal. We did not see any statistically significant evidence for scintillation mechanism damage with either method. The effect is consistent with zero, and the upper limit is 0.5% at 95% C.L.

Key word: scintillation, radiation damage, lead tungstate PACS 61.80.-x 29.40.Vj.

Аннотация

Батарин В.А., Батлер Д., Чен Т. и др. Изучение возможного нарушения сцинтилляционного механизма в кристаллах PbWO_4 после пионного облучения: Препринт ИФВЭ 2004-40. – Протвино, 2004. – 11 с., 9 рис., 2 табл.

Представлены два независимых метода для изучения возможного нарушения сцинтилляционного механизма в кристаллах вольфрамата свинца при их облучении пучком пионов с энергией 34 ГэВ. В первом методе 10 кристаллов облучались одновременно в течение 30 часов узким пучком, воздействовавшим лишь на малую область в каждом кристалле. Наблюдалось влияние облучения на неоднородность световыхода по длине кристалла. Его локальное изменение указывало бы на нарушение сцинтилляционного механизма. Во втором методе измерялся световыход двумя фотоумножителями, расположенными на боковых гранях кристалла. Так как эти фотоумножители регистрируют только свет, рожденный в локальной области, влияние изменения прозрачности должно быть минимальным. Мы не обнаружили сколь-нибудь статистически значимого подтверждения нарушения сцинтилляционного механизма ни одним из методов. Эффект сравним с нулём с верхней оценкой 0.5% на уровне достоверности 95%.

1. Introduction

A high precision electromagnetic calorimeter (EMCAL) will add to the exciting physics capabilities of BTeV [1] by detecting photons and electrons with excellent energy resolution ($\sigma E/E \simeq 1.8\%/\sqrt{E}$) [2, 3]. It will consist of more than 10,000 lead tungstate (PbWO_4) crystals. One of the most important challenges to maintaining the high intrinsic resolution this system is to keep the absolute energy calibration better than 0.2%.

The system consists of crystals glued to photomultiplier tubes (PMT) and monitored using a pulsed light source connected to the crystals with a thin transparent fiber. There are several inherent sources of instability in this system. First of all the gain of the PMT's may change; this we monitor using red light which is significantly less sensitive to changes in the crystal transmission than blue light[4]. Secondly, the light outputs from the crystals may also change. For example, the light output decreases by 2% for a temperature increase of 1^0 C ; we will maintain the temperature of the crystals constant to 0.1^0 C to reduce this effect to a manageable level.

Another important reason for the light output of the crystals to change is irradiation. Many BTeV crystals will be exposed to radiation of less than 1 rad/hour, but some will receive 20 rad/hour. Even when the radiation dose rate is only a few rad/hour, the crystals will suffer radiation damage, and as a result, the light output will decrease [5]. The light output loss is believed to be due to the degradation in the transmission of light inside the crystal, and not due to the degradation of the light emission. We can monitor the transmission loss (TL) by measuring it directly using light from a stable light source. On the other hand, if there is light emission loss (EL), this cannot be measured easily.

The BTeV crystals will be calibrated using electrons from the data, whose momenta are measured in the tracking devices (in-situ calibration). Collecting enough electrons in each crystal will require only several hours of running. In fact, those crystals that will be exposed to high radiation and will likely to suffer most severe damage can be calibrated as often as every hour, because the electron collection rate is highest in those crystals. Since the in-situ calibration measures the light output directly, it reflects the losses in the emission as well as in the transmission. Thus we need only worry about calibrating crystals using the light source for the period of data taking between the in-situ electron calibrations.

In this paper we investigate the possible change in light emissions in the crystals which would be a more serious change than the loss of transmission as the transmission does recover in time [5]. This paper reports results of two such studies.

The transmission loss is thought to be due to formation of color centers, each of them is caused by an electron trapped in a crystal defect. The trapping happens when the electron absorbs radiation energy and jumps to higher energy states which exist around the crystal defect. Even though valence electrons in the PbWO_4 (PWO) crystal need to absorb a relatively large energy corresponding to a short wavelength photon to be able to jump to higher allowable energy levels, this excited electron needs less energy to do so, and the corresponding photon wavelengths often fall in the visible range. This causes the crystal to absorb light. For the transmission loss to last, these trapped electrons must be in metastable states. In PWO crystals, the relevant metastable states have lifetime short enough at room temperature so that when the radiation dose is reduced, the transmission will recover gradually (hours to 10's of hours).

Emission may be reduced if light-emitting atom is changed under irradiation, due to possible transformation of the nucleus of an atom in the nuclear reaction. One of the consequences is that such transformation, if happens, is likely to be of permanent nature, which would lead to a cumulative effect.

Indirectly, we have already addressed the issue in our previous study [5]. We measured non-uniformity of the light output along the crystal by exposing the crystals to a muon beam perpendicular to the axes of the crystals. Then we rotated the crystal matrix so their axes were along the beam and irradiated the crystals with a pion beam for 10 days. After the irradiation we rotated the crystal matrix by 90° again and made another scan with muon beam. The non-uniformity of the light output in the front part of crystal (3-10 radiation lengths), where dose rate from pions was varying within a factor of two, was about 0.5%/cm. The non-uniformity did not change after an absorbed dose up to 4 krad, which caused the signal loss of up to 30%. It was an indirect proof that we did not see scintillation mechanism damage.

In previous studies no evidence of EL was found in PWO crystals after their irradiation with gamma-source [6]. In this paper we present two independent methods of direct study of possible scintillation mechanism damage.

Dr. R.Y. Zhu proposed the main idea of the first method [7]. This method relies on the light output difference between irradiated and non-irradiated zones of a long crystal, after exposition to a narrow pion beam traveling in the transverse direction relative to the crystal length. In this method we irradiate a small section of a crystal along its length using a pion beam, and measure the light collection uniformity both before the irradiation and immediately afterward. If one assumes that the loss is due only to transmission, the uniformity should not be affected very much since the light from anywhere in the crystal will travel in the crystal at least once. Thus, it is affected evenly regardless of where the light is emitted in the crystal. However, if there is loss due to EL, it should only effect light from the irradiated section. Therefore, if one observes localized loss in the area where the crystal was irradiated, such loss can be attributed to EL.

In the second approach, we mounted two PMT's on the sides of a crystal and one at the end of the crystal. We presumed that if a muon travels along the axis of the crystal, only the light emitted near PMT's will reach the PMT's. The reason is, if the crystal surface is optically flat, light from the other part of the crystal has to travel a very long distance before it reaches one

of the PMT's. If this assumption is correct, then the detected light loss can be attributed to the EL effect.

The studies were carried out in the IHEP test beam facility [5].

2. Method I

2.1. Experimental setup

In this study we used both pion and muon beams crossing an array of PWO crystals in the perpendicular direction relative to the crystal lengths. Fig. 1 shows how the crystals were placed relative to the beam as seen from the top. Five of the 10 crystals were produced by Shanghai Institute of Ceramics (SIC) and the other five crystals were produced at Bogoroditsk Techno-Chemical Plant (BTCP). We used an intensive pion beam to irradiate only the middle section of the crystals, while the muon beam was used to measure the light output uniformity of the crystals along their lengths before and after irradiation. To do this, the crystal array was moved so that the muon signal can be measured in any area of a crystal.

The crystals were irradiated for about 30 hours with a beam intensity of $2.6 \cdot 10^6$ pions/spill. Each spill lasted for 1.5 sec, with the full cycle of 9 seconds. About 95% of the pions were contained in an area of 2 cm in width and 6 cm in height.

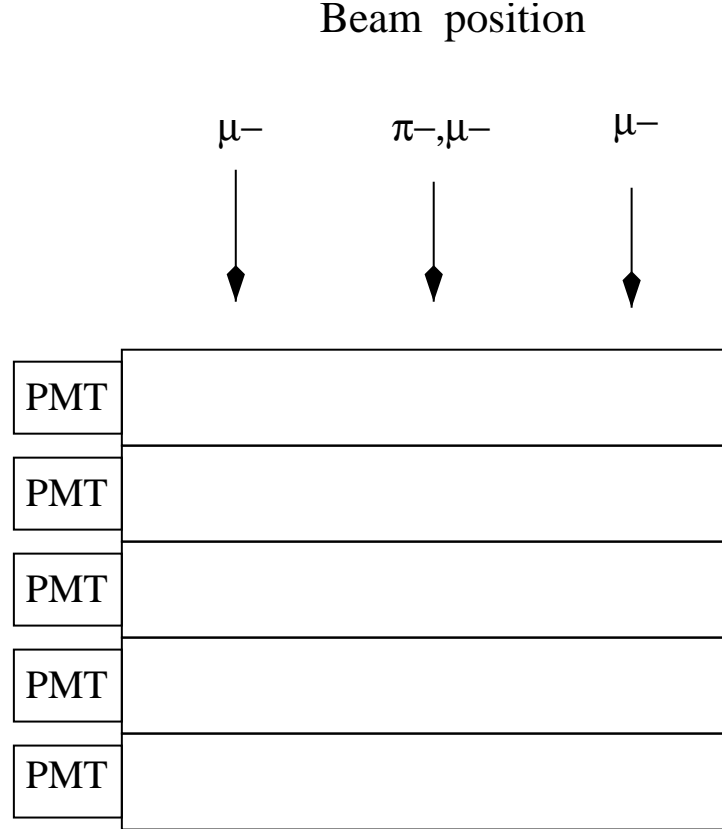


Figure 1. The layout of the crystals in the first study and the beam positions (plan view). The crystals are 27 mm^2 in cross section and 220 mm long.

2.2. Monte-Carlo simulations of dose rate

To be able to predict how the light transparency inside the crystal varies, we need to know the absorbed dose distributions of the pion beam. The dose rate distributions along each crystal in the crystal matrix has been studied by GEANT3 simulations. Fig. 2a shows a lateral dose rate profile during the pion irradiation runs for crystal 3(BTCP). Also, Fig. 2b shows the maximum dose rate for each of the ten crystals.

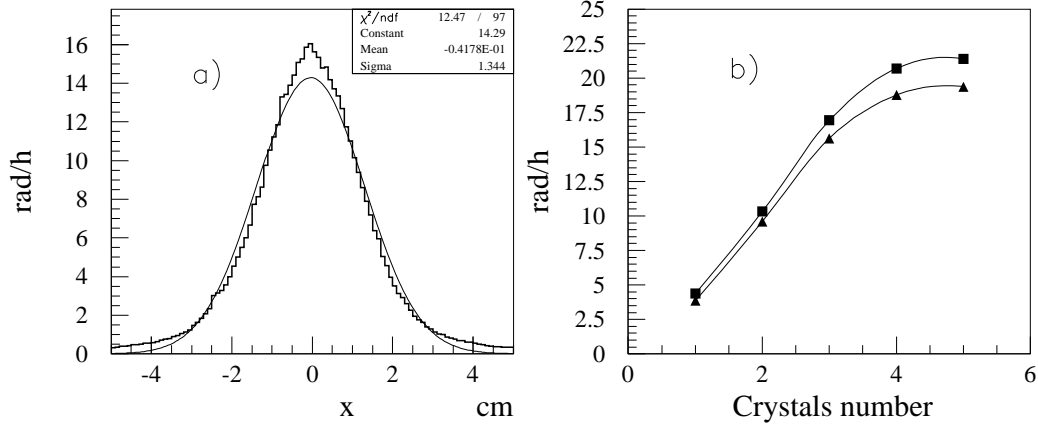


Figure 2. (a) The lateral dose rate profile during the pion irradiation runs for crystal 3 (BTCP). The position $x = 0$ corresponds to the center of the beam. (b) Maximum dose rate. The filled squares indicate SIC crystals in the top layer, and filled triangles indicate BTCP crystals.

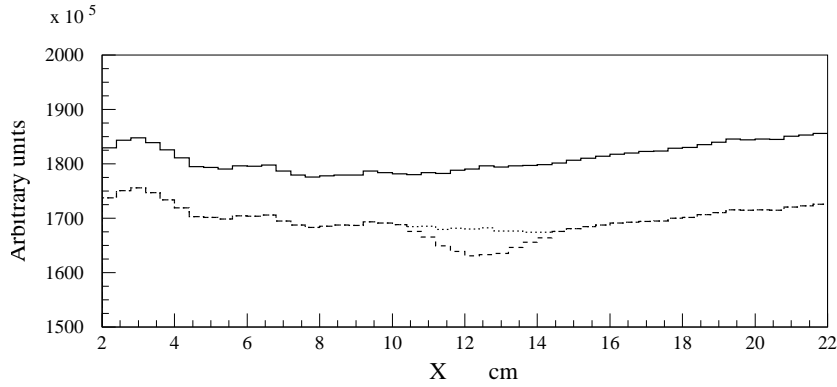


Figure 3. Light response uniformity before (solid line) and after (dashed line) irradiation. The dotted line indicates the response when the scintillation mechanism damage was not included. Monte-Carlo simulation.

To understand possible effects qualitatively, a light collection model was developed and incorporated in the GEANT3 simulation in order to study possible changes in the light response uniformity due to scintillation mechanism damage. We assumed that crystals have ideal optical properties, thus anisotropy and diffuse reflection were not included.

The light response uniformity depends on both light transmittance and the local light emission. The zone of the color center formation was assumed the same as shown in Fig. 2, a Gaussian distribution with σ equal to 1.3 cm. Relative light transmittance was estimated as the ratio of the crystal response to muons after and before irradiation. For illustrative purposes we assumed that the scintillation mechanism degradation was 3 % at the point of the maximum absorbed dose. A proportionality between absorbed energy and degradation of the scintillation mechanism was introduced.

Fig. 3 presents results of the simulation. The upper curve (solid) shows the light output as a function of the distance to the PMT and the lower curve (dashed) shows the light output after irradiation that results in a loss of transmission and with 3% damage to the scintillation mechanism. The dotted section is the response without damage to the scintillation mechanism.

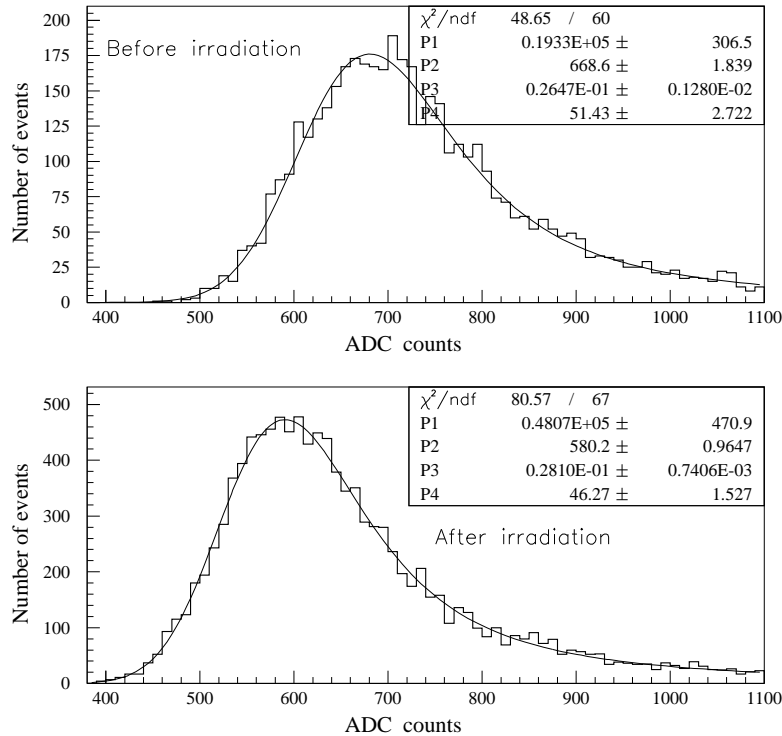


Figure 4. Energy loss distributions for minimum ionizing particle for crystal 2 (BTCP) before and after irradiation in the first method. The data are fitted by a convolution of the Gaussian and Landau distributions. The fit parameters are as follows: P1 — the normalization factor; P2 — the most probable signal (MOP); P3 — the inverse value of the Landau distribution FWHM; P4 — the Gaussian sigma.

2.3. Results and discussion

The position of the muon track going through a crystal was reconstructed using the drift chambers [2]. The pulse-height distribution collected for each selected region along the crystal length was fitted by a convolution of the Landau and the Gaussian distributions to obtain a peak position. An example of how we determine the peak position of the energy loss distribution for minimum ionizing particle is shown in Fig. 4.

After an estimation of the muon peak position, the light response curves for different crystals were obtained. The results for one such crystal from BTCP are shown in Fig. 5. The data were fitted to the 3-rd degree polynomial function. In this figure, the arrow and the solid triangles mark the region of the crystal, from 11 cm to 15 cm, irradiated by pions. It was excluded from the fit of the data after irradiation. We observed no additional light loss in this area showing that we are not sensitive to any scintillation damage, at our level of radiation.

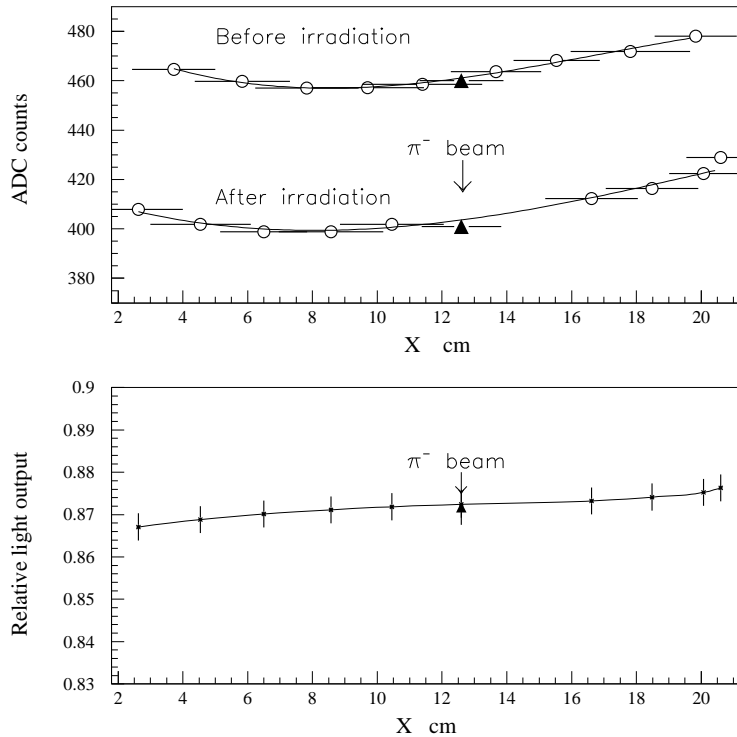


Figure 5. A typical light response uniformity before and after irradiation. Maximum intensity for pion beam is at the $X=12.6$ cm. PMT position is at $X=0$ cm.

We assume that one can factorize the function of the light output at any scanning muon position x in the crystal into two parts. The first part depends on only TL of the light, which goes from the point x to the phototube directly and indirectly by reflecting from the crystal end. The second part, $s(EL,x)$, depends on only EL at the beam position x .

By taking the ratio of the light output as a function of x before (index b) and after (index a) radiation, we can isolate the effect of loss of scintillation light. The EL part of the relative light

output then is given by

$$rs = \frac{s^a(EL, x_\pi)}{s^b(EL, x_\pi)}, \quad (1)$$

where x_π is the pion beam position during the crystal irradiation.

The rs values for 10 crystals are shown in Fig. 6. There is no light output alteration due to scintillation mechanism damage if rs is equal to 1. In our $\approx 0.5\%$ accuracy range one can say, that for each out of 10 crystals we could not see an emission loss after pion irradiation. The value $1 - rs = (0.20 \pm 0.15)\%$ when averaged over these 10 crystals.

We conclude that if the scintillation mechanism damage exists, the degradation of intrinsic scintillation light yield after pion irradiation is less than 0.5% at a confidence level of 95%. Fig. 7 demonstrates a total relative light output in the zone of irradiation.

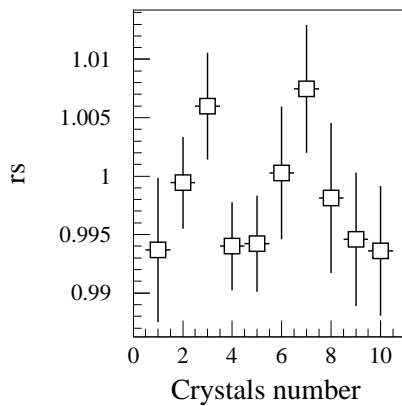


Figure 6. The relative emission light part of the total relative light output. First five crystals from Bogoroditsk, the second five crystals from SIC (tapered).

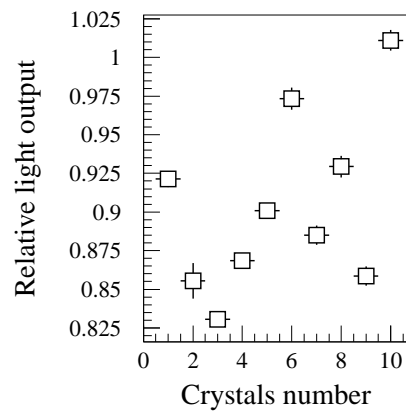


Figure 7. The total relative light output in the zone of irradiation.

3. Method II

3.1. Experimental setup

In this study, we attached 3 one-inch phototubes (Hamamatsu 5800) to a crystal. Fig. 8 shows the device layout. The crystal was irradiated by a pion beam traveling along its length. In addition, we used the same LED-based light transparency monitoring system that we used at our test beam facility [8]. The crystal was wrapped in a black paper to minimize diffusive reflections. The far PMT was coupled to the crystal using optical grease, while the side PMTs were coupled with an air gap. A light from the LED was injected into the crystal via an optical

fiber. The angle between the crystal's surface and the optical fiber was 75° . The side phototubes were placed midway along the crystal.

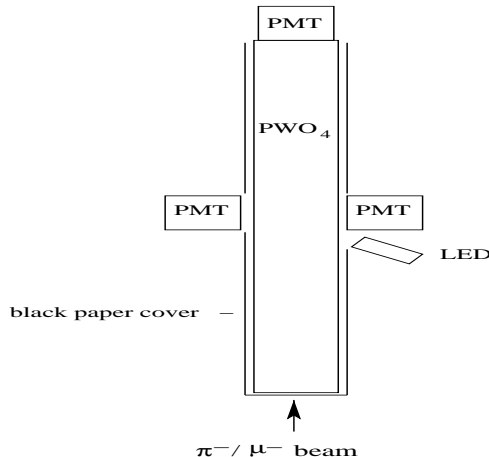


Figure 8. The layout of crystal and PMT's for the direct-light measurements (plan view).

Scintillation light produced near the side PMTs has to travel only a few cm before it enters one of these PMTs. We assume that light from other parts of the crystals won't even reach these PMTs. Then, the effect of transparency degradation in the signal detected by the side PMTs should be small. Transmission degradation was monitored by the light source. We irradiated the crystal for 8 hours with a beam intensity of $2.6 \cdot 10^6$ pions/spill, which corresponds to the average dose rate in the center of the crystal of ≈ 15 rad/hour.

3.2. Results and discussion

In this method we compared crystal light output caused by muons and measured by the side phototubes before and after irradiation. This is similar to measurement of the light output from a thin scintillating sample, when we do not sense light transmittance degradation. A position of a muon track passing through the crystal was reconstructed using the drift chambers. Muons in the area of $4 \times 4 \text{ mm}^2$ in the center of the crystal were used to measure light output.

The muon signal distributions, fitted by the convolution of Landau and Gaussian distributions, are shown in Fig. 9. The ratios of the amplitudes after irradiation to those before irradiation for the muon and the LED signals are presented in Table 1. The LED signals did not change after irradiation in either of the side phototubes. This is expected, since we assume that the light going into the side PMT's travel only small distances and the LED signal should be insensitive to the transparency loss. At the same time we did not find any statistically significant light loss in the muon signals. To treat the results of the second method correctly it's important to take into account a contribution of the light from far points of the muon track.

Because in the real life the crystal's surface is not perfectly flat, there exists diffusive reflection of light in addition to the geometric total internal reflection. Some part of the scintillation light, particularly that which initially travels in the direction parallel to the crystal length, may travel a long distance before it reaches the side PMT's. This component will suffer transmission loss, even though the other component — light reaching the PMT's more directly — may not suffer

transmission loss. We call the former component, indirect light. We can estimate its contribution into the measured light output loss.

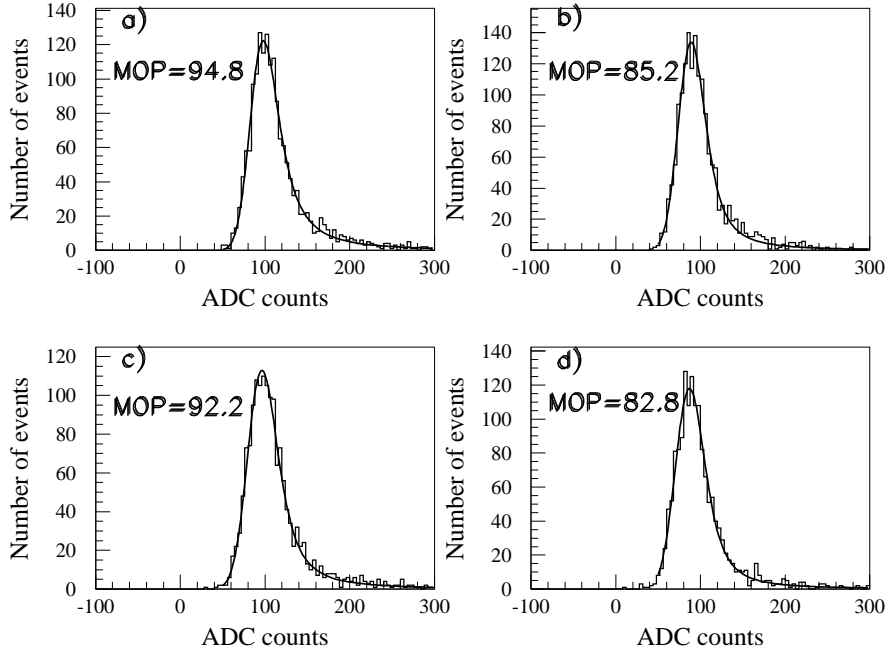


Figure 9. Fit results for the distributions of the light outputs which were detected by the side phototubes in the second method. The same fit as in Fig. 4 was used: a) left PMT before irradiation; c) left PMT after irradiation; b) right PMT before irradiation; d) right PMT after irradiation.

The third row of Table 1 shows attenuation of the LED signals in the far PMT, although in the idealized case, light from the LED would not reach the far PMT. From the pulse-height spectra of LED signal, one can estimate the number of photoelectrons if the variation is solely due to the photoelectron statistics. Then the number of photoelectrons per ADC count equals the ratio mean/σ^2 . Table 2 presents portions of light in photoelectrons from different sources. If we divide the number of photoelectrons for the far PMT by the number of photoelectrons for the left PMT (see Table 2), we obtain that $(0.7 \pm 0.1)\%$ of blue LED light reaches the far PMT. In our dedicated measurements at a stand after the accelerator run we found that this mean value is about the same as the part of indirect muon scintillation light which reaches the side PMTs. We assign conservatively the error of our estimate as 100%. It gives us $(0.7 \pm 0.7)\%$ for this part. From our previous measurements, we learned that the light input into a PMT drops by a factor of two if there is an air gap between a crystal and a photocathode instead of using optical grease. This decreases our estimated value of the contribution of indirect light in the side PMT's from muon scintillation from $(0.7 \pm 0.7)\%$ down to $(0.35 \pm 0.35)\%$.

This suggests that the indirect light going into the side PMT's is 0.35% of the light going into the far PMT. *i.e.* of about 50 photoelectrons in the side PMT's, (3.6 ± 3.6) (or $(7.2 \pm 7.2)\%$) are indirect. From the LED data, we estimate that the indirect light into the far PMT lost

10.5% after irradiation. Assuming that the same fractional loss applies to the indirect light into the side PMT's, we conclude that $(0.76 \pm 0.76)\%$ of the light in the side PMT's will be lost due to the transmission loss. Subtracting this number from $(2.8 \pm 1.4)\%$ (see Table 1), we can finally estimate the light loss as $(2.0 \pm 1.6)\%$ which is consistent with zero.

Table 1. The ratios of the amplitudes for muon and LED signals after and before pion irradiation in the second method.

PMT	muon	Blue LED
Left	0.973 ± 0.013	1.000 ± 0.001
Right	0.972 ± 0.014	1.007 ± 0.002
Far	0.920 ± 0.007	0.895 ± 0.009

Table 2. Estimation of the numbers of photoelectrons before irradiation in the second method.

PMT	muon	Blue LED
Left	50.0 ± 3.8	7000 ± 500
Right	50.9 ± 3.2	5200 ± 300
Far	1039 ± 73	45.6 ± 2.9

4. Conclusion

The first direct study of possible damage to the scintillation mechanism of lead tungstate crystals after hadron irradiation at moderate dose rates was carried out for the BTeV experiment. We have studied possible effects using two independent methods. We did not see any evidence of the scintillation mechanism damage over period of 8 to 30 hours in the either method. This effect is consistent with zero and the upper limit for the absorbed dose up to 600 rad is 0.5% at 95% confidence level.

This justifies the BTeV EMCAL calibration scenario that will rely on the in-situ calibration with particles produced in physics events, at least once a day, and on using monitoring with a light pulser in between.

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