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Abstract

The comparative study of radiation hardness of KRS, NBW and PWO crystals used in the calorimetry of high energy particles is performed. Their spectral transparency is measured before and after irradiation by a big doses ($\approx 100 Mrad$) from Co^{60} γ-source. The scintillating crystal PWO did not lose practically its transparency whereas among cherenkov radiators KRS and NBW the last one had better radiation resistance. The influence of irradiation of KRS and NBW crystals by high energy (up to $25 GeV$) photons and electrons on their transparency was also investigated at doses $10 - 100 Mrad$.

1 Introduction

The transparent heavy monocrystals of Talium Halogenid $TlCl - TlBr$ (named KRS), Bismuth-Tungstate $NaBi(WO_4)_2$ (NBW) and Lead-Tungstate $PbWO_4$ (PWO) are widely used in high energy physics for electromagnetic calorimeters manufacturing.

The application of these materials allows to construct compact detectors which give the possibility to measure with good accuracy the energy of electrons and photons and their hit point coordinates in a detector. The compactness of such detectors is due to small values of radiation length ($X_0 \approx 10mm$) and Moliere radius ($R_m \approx 20mm$).

The main physics-chemical properties of these crystals are given in the Table 1.

The advantage of detectors based on these crystals is their high radiation resistance. Since the particles are detected through cherenkov or scintillation light produced by secondary electrons and positrons of electromagnetic shower the optical transparency of crystals for corresponding wave length is an important crystal characteristic. While plastic scintillators or heavy glasses lose their transparency after receiving the irradiation dose of $\approx 1Mrad$ the similar phenomena arise in the crystals at absorbed doses of two order higher values.

Table 1. Properties of KRS, NBW and PWO crystals.

Crystal	KRS-15	NBW	PWO
Chemical composition	$TlCl(78\%)TlBr(22\%)$	$NaBi(WO_4)_2$	$PbWO_4$
Light emission	cherenkov	cherenkov	scintillation
Density $\rho(g/cm^3)$	7.65	7.57	8.3
Refractive index	2.2	2.15	2.2
Radiation length $X_0(mm)$	9.2	10.3	9.0
Moliere radius $R_m(mm)$	20.8	23.8	20.0
Melting temperature (^oC)	420	920	1123
Transmission edge $(nm) \geq$	410	380	350
Emission peak (nm)	-	-	480
Critical energy $E_c(MeV)$	8.95	9.75	-
Decay time $\tau(ns)$	-	-	2.1, 7.5, 26

The first description of the cherenkov detector with radiator made of $TlCl$ monocrystal was given in [1]. Later the KRS crystals which are the composition of $TlCl$ and $TlBr$ were used in the detectors [2]. The properties of halogen crystals were described in [3]. The KRS-15 crystal consisting of 78% $TlCl$ and 22% $TlBr$ happened to be the most suitable for cherenkov detectors exploited at hard radiation conditions.

The luminosity monitor of the H1 experiment at ep-collider HERA at DESY is an example of KRS-15 crystals use in high energy physics. The monitor worked successfully in 1992-1998. By 1999 some crystals get doses up to several tens of $Mrad$ and partly lost their transparency. 5-fold increase in the luminosity is planed after HERA upgrade 2000. This will lead to high level of detector irradiation ($\approx 100Mrad$ per year). The task to search for new materials which would allow to elaborate more radiation hard monitor is very actual.

A possible solution of this problem is the use of SPACAL type detector with radiation resistant quartz fibers [6] or the exchange of KRS-15 crystals in the luminosity monitor for more radiation hard ones.

The present work is devoted to comparative study of properties of KRS, NBW and PWO crystals which can be used for development of radiation hard detector.

The NBW crystals (as KRS) are cherenkov radiators. The studies show that NBW have rather high radiation resistance [7]. They are used for a long time in the luminosity monitor of HERMES experiment at HERA [8] and also in electron tagger of H1 detector.

PWO crystals are scintillators. They are planed to be used in the electromagnetic calorimeter of the CMS detector [9] at LHC collider and in the other experimental facilities. The stability of their optical characteristics under the irradiation depends on the chemical admixtures and the crystal structure defects. It is known that the radiation damages in these crystals begin to arise already at doses of several tens of Rad; but the small decrease in the transparency is not irreversible: it is partly restored after several days. As for the high doses ($> 10Mrad$) the data for PWO are uncertain: firstly there is considerable dispersion in results the irradiation induced light absorption studies and secondly the transparency change depends on the purity of raw materials from which the crystal was manufactured and on the admixtures in the crystals. The measurements [10] showed that the transparency of the crystal of 250mm length was lowered by 12% at the peak emission after irradiation by doses of $10Mrad$.

To chose the materials which are the most preferable for the work in heavy radiation environment (doses worse then 100Mrad) at high luminosity experiments at present accelerators it is actual to perform the comparative study of the radiation hardness of KRS, NBW and PWO crystals in the identical conditions.

2 Study of the crystal radiation hardness

2.1 The investigation of KRS-15 radiation resistance at LPI synchrotron

The influence of KRS crystal irradiation by energetic photons on its transparency was studied at PAKHRA electron synchrotron of P.N.Lebedev Physical Institute (LPI) at doses $\approx 10Mrad$. The crystal disk samples of 35mm diameter and 5mm thickness were exposed at bremsstrahlung beam of maximal energy $E_{max} = 850MeV$ during 48 hours.

The absorbed dose was estimated as follows. The bremsstrahlung energy stream through the 10mm diameter collimator was measured by quantometer. The samples were placed on the front collimator wall at the distance several cm from the beam axis. The γ-stream hitting the sample was calculated taking into account the angular and energy distributions of bremsstrahlung photons emitted. This stream of photons with energies from the threshold of electron-positron pair production to maximal energy $E_{\gamma max} = 850MeV$ has value of $3.8 \cdot 10^{12}\gamma/min$. Inside the KRS crystal these gammas produce e^+e^--pairs which loose the part of their energy on ionization in the sample. The probability of photon conversion for the sample of 5mm thick is equal to 0.32. Then the number of pairs produced in the sample is equal to $1.22 \cdot 10^{12} e^+e^- - pairs/min$. Since the ionization losses for relativistic particles are close to $\approx 2MeV/g/cm^2$ the energy of two ionizing particles absorbed in the sample is equal to $9.4 \cdot 10^{12} MeV/min$. (We suggest that ionizing particles are created in the middle of the sample and pass only half of its thickness). Thus the absorbed energy per 1Kg of the sample material is equal to $12Mrad$ ($7.3 \cdot 10^{17} MeV/kg$) for 48 irradiation hours, that is the irradiation power was $0.24 Mrad/hour$. Real absorbed dose will be obviously bigger because of beam background, compton scattering and induced radioactivity in the samples and nearby materials.

The sample transparency was measured by transmission of diode light with wavelength $\lambda = 626nm$ through the sample. The schematic layout of the setup is given in Fig 1. Results of the measurements before and after irradiation of samples coincide within the accuracy of

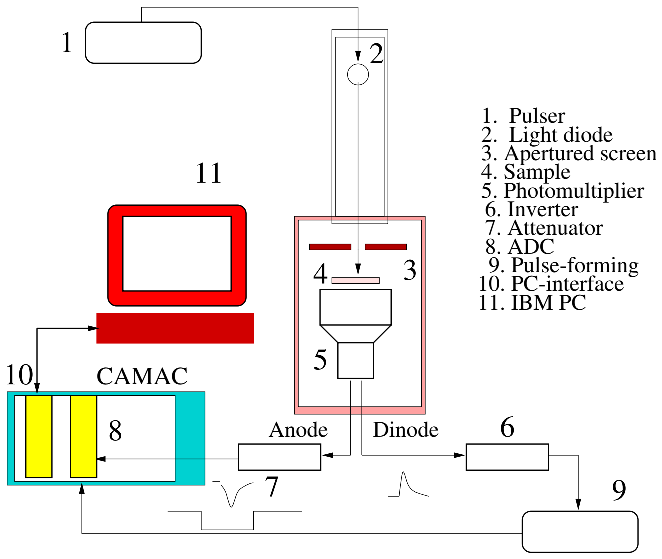

Figure 1: The layout for transmittance coefficient measurements using lightdiode.

measurements ($\approx 5\%$).

At the same time and the same conditions the samples of lead glasses (TF-1 and TF-2) were irradiated. They became practically opaque after several hours of irradiation. Thus KRS crystals can stand $10Mrad$ level of irradiation.

2.2 Radiation damage of KRS and NBW crystals at HERA collider

The KRS and NBW crystal are used in the H1 luminosity monitor at HERA *ep*-collider as the radiators of cherenkov spectrometers [5]. The luminosity is measured by detection of photon and electron from the process of bremsstrahlung radiation of $27.5GeV$ electrons (or positrons) [1] colliding with $820GeV$ (now $920GeV$) protons:

$$e + p \rightarrow e' + \gamma + p. \tag{1}$$

The monitor consists of photon and two electron detectors (tagger33, tagger44) based on hodoscopes of cherenkov total absorption shower counters with photomultipliers (PMT) readout.

The tagger33 is placed downstream the electron beam at the distance $\approx 33m$ from the ep-interaction point and contains 49 (7x7) KRS crystals of the size $20\text{x}20\text{x}200mm^3$. The tagger detects electrons with energies $7 - 20GeV$. Background electrons and protons and rescattered synchrotron radiation also hit the crystals. During 6 years of HERA operation the DESY dosimeters placed on the tagger get a dose $\approx 20Mrad$. The really absorbed by crystal dose can exceed this value in several times. The crystals (5 of 49) placed in the area of the highest irradiation during accelerator beams tuning or in the case of beams lost became slightly dark whereas the others placed nearby stayed quite transparent. Since the crystals used in this detector belong to different batch of production the strong variation in the radiation damage is probably due to manufacturing technology and to the difference in controlled or noncontrolled admixtures. Some dark inclusions are seen in the damaged crystals.

More severe radiation environment exists for tagger44 placed at distance $\approx 44m$ downstream the interaction point. This detector tags electrons with higher energies (24-26GeV) then tagger33 and subjected to unexpected irradiation during injection, beam bump or even luminosity runs. Also the stream of recoil electrons of bremsstrahlung process is more collimated in this case. The tagger had 6 (3x2) $200mm$ long KRS crystals. Before middle of 1996 it occupied the stationary position at the distance $\approx 26mm$ from the axis of circulating electron beam. Later the corresponding section of accelerator beam chamber was made movable in order to approach the tagger as close as $12mm$ to the beam axis after the stable beams operation was declared. This helped with three-fold counting rate increase but at the same time led to more heavy irradiation of the tagger and to more pronounced radiation damage. The loss of crystal transparency because of the damage can be estimated through the measurement of so called calibration coefficients (CC) which are determined from the energy balance in the process (1): $E_e = E_\gamma + E_{e'}$, and used to multiply the PMT amplitudes to take into account weakening of light output from the crystal. Fig 2. shows time variation of CC for the most "radiation hot" crystal module 3 of the tagger44 hodoscope. The CC watches the integrated behaviour of spectrometric channel parameters what include the loss of crystal transparency, degradation of PMT, some changes in electronics and high voltage supply. The point **A** in the figure corresponds to the end of the work in stationary regime and **B** - to the begining of the work with the tagger position closer to the electron beam. The weak CC general increase ($\approx 3\%$ for 34 days) before the date **A** reflect slight darkening of the crystal. The oscillations ("cogs") around general CC change are connected with behaviour of PMTs gain during single electron fills (Luminosity runs); they disappear at the periods when there are no e-beams in the HERA (dates between **A** and **B**). Begining the date **B**

[1] Below the term electron is used for positron as well.

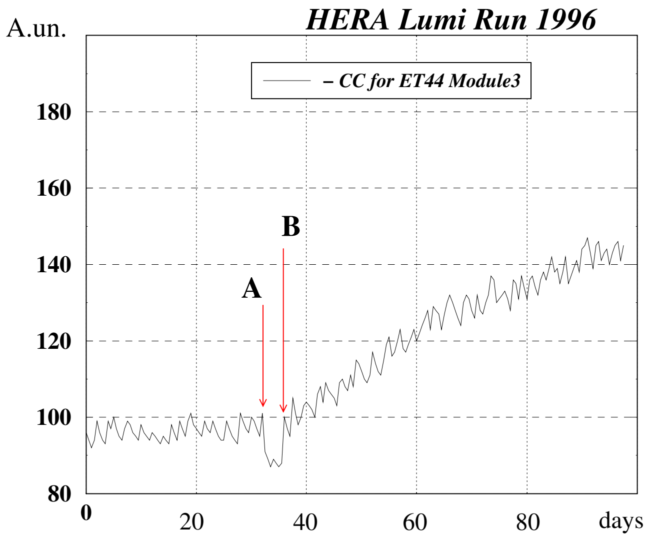

Figure 2: Time dependence of the calibration coefficient CC.

the CC reveal the pronounced rise which reach the value of $\approx 40\%$ after 60 days of HERA operation and which is connected directly with aggravation of the KRS optical properties because of radiation damage. Thus the radiation hardness of KRS crystal is close to several tens of $Mrad$.

In 1998 the crystals in the tagger44 were exchanged for the more radiation hard NBW crystals. The glass dosimeters installed in the detector show the irradiation dose $2Mrad$ after one year of the tagger operation. The absorbed dose recalculation for the crystal gave the result $\approx 100Mrad$. One of NBW crystals placed in the site with high level of radiation turned from light yellow to light brown. So the hundred $Mrad$ dose is critical for the optical transparency of these crystals what confirms the results in the NBW radiation hardness study [7].

2.3 Comparison of monocrystals radiation hardness at high radiation load

It is interesting to study radiation resistance of KRS crystals at high doses and compare in the same conditions of irradiation the optical properties of KRS, NBW and PWO crystals. To do this we irradiate simultaneously several samples of the monocrystals.

KRS-15 samples has the form of 30mm diameter disk of 10mm thickness. NBW and PWO samples are rectangular parallelepipeds of 22x22x60mm^3 and 22x22x10mm^3 size respectively. KRS crystals were manufactured at Pishma Optical Factory, NBW - at Institute for Synthesis of Raw Materials (Alexandrov), PWO - at Bogoroditsk Techno Chemical Plant.

The samples were irradiated at powerful Co^{60} γ-source at the Institute of General and Nonorganic Chemistry. $100Mrad$ dose was achieved after 40 hours of irradiation. (The dose power was $2.5Mrad/hour$). As a result of irradiation the sample temperatures rose to several tens of grad (C^0). The irradiated samples and nonirradiated crystals of the same size and batch were inspected using the spectrophotometer. The transmission spectra were measured for the wave length range of highest photomultipliers sensitivity. The results are given in the Fig.3, 4 and 5. It is seen that KRS crystals are the least radiation resistant; the

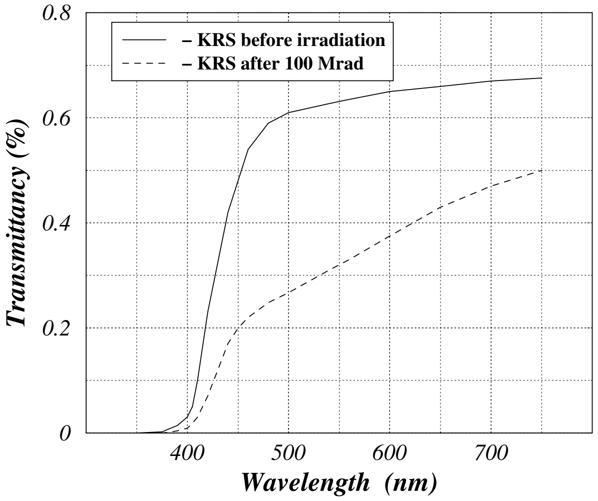

Figure 3: Transmission spectra of KRS-15 sample before irradiation (solid line) and after (dotted line).

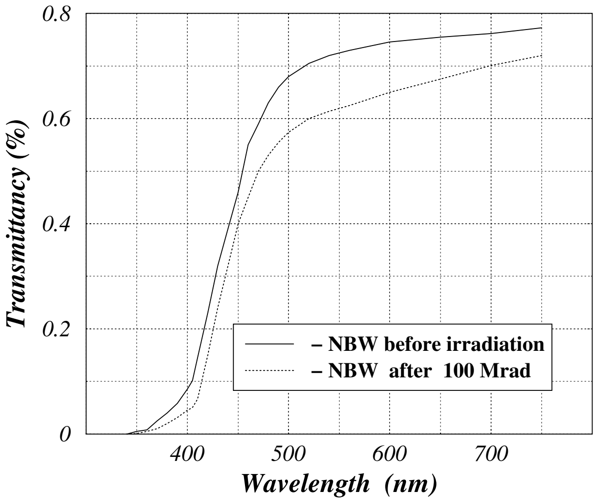

Figure 4: The same as Fig.3 but for NBW sample.

100Mrad irradiation led to seen by eyes sample darkening. The PWO crystals happened to be the most radiation hard: obtained transmittancy for irradiated and nonirradiated samples coincide within the measurement accuracy ($\approx 1\%$) (some visible excess lays is within this accuracy). The similar result was obtained for the doped by Y PWO samples [11].

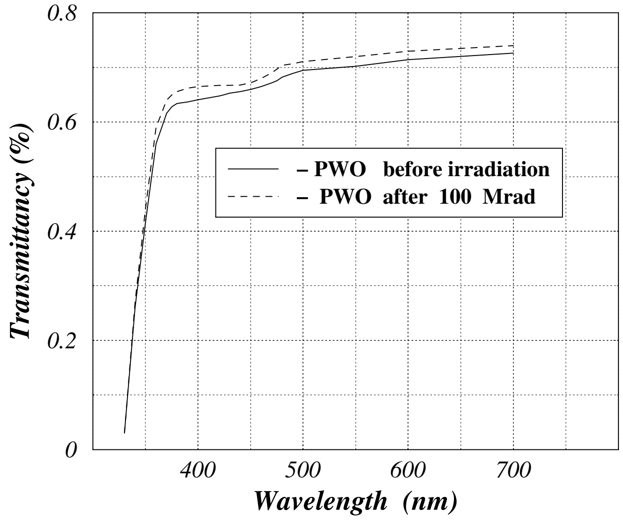

Figure 5: The same as Fig.3 but for PWO sample.

The samples transmittance coefficients T were also measured for light wave length $\lambda = 626nm$ using the device similar to one shown on the Fig.1 with FEU-68 photomultiplier as a light detector. T is defined as the ratio of photomultiplier amplitudes obtained with diode light transmission through the sample and without the sample. The results of the study are given in the Tables 2a and 2b for nonirradiated KRS, NBW, PWO(3), PWO(4), PWO(5) samples and for irradiated KRS, NBW, PWO(1), PWO(2) samples.

Table 2a. Transmittance coefficient T for nonirradiated crystals.

Crystal	KRS-15	NBW	PWO(3)	PWO(4)	PWO(5)
T	0.81 ± 0.01	0.87 ± 0.01	0.85 ± 0.005	0.84 ± 0.02	0.83 ± 0.01

Table 2b. Transmittance coefficient T for irradiated crystals.

Crystal	KRS-15	NBW	PWO(1)	PWO(2)	PWO_{mean}
T	0.50 ± 0.01	0.78 ± 0.01	0.83 ± 0.01	0.81 ± 0.01	0.82 ± 0.01

The mean T value for nonirradiated PWO samples is equal to T=0.84 ± 0.02 what is close to T_{mean} for irradiated crystal (Table 2b). So these measurements support the conclusion that PWO crystals are the most stable against high doses of irradiation.

3 Results discussion and conclusion

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A) The radiation hardness depends on the purity of raw materials. This is seen especially clear from the history of development of PWO crystals which radiation hardness became better as the technology of their production has been improved.

B) Among studied hier monocrystals KRS-15, NBW and PWO the last one is the most radiation hard. Its transparency stayed the same (within the measurement accuracy $\approx 1\%$) after the irradiation by $100 Mrad$ dose. Probably the our sample had the better quality then one used in the study [10] where PWO transparency degradation were seen at lower doses.

C) The result obtained for NBW agrees with published earlyer data [10] for $100 Mrad$ irradiation dose.

D) KRS-15 crystal turns out to be less radiation resistant then NBW and PWO.

Acknowledgements

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