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ABSORBED DOSE IN SCINTILLATORS OF ZERO DEGREE CALORIMETER AT IRRADIATION BY PB NUCLEI WITH 157.7 GEV/NUCLEON ENERGY

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For the first time the absorbed doses in scintillators of hadronic calorimeter are measured and compared with the results of simulation of the Pb-Pb interactions at 157.7 GeV/nucleon energy. Measurements were performed during the Pb-run of WA-98 experiment at CERN SPS using the Zero Degree Hadronic Calorimeter (ZDC). The efficient way is proposed to increase the calorimeter resource by means of combination of the recovery of optical properties of the scintillator + light guide system and of the decrease (shifting) of the maximum dose value.

The investigation has been performed at the Laboratory of High Energies, JINR.

Поглощенная доза в сцинтилляторах ZDC при облучении ядрами Pb с энергией 157,7 ГэВ/нуклон

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Впервые при Pb-Pb взаимодействиях и энергии 157,7 ГэВ/нуклон измерены поглощенные дозы в сцинтилляторах адронного калориметра, которые сравниваются с результатами расчетов. Измерения выполнены на ZDC во время WA-98 эксперимента на SPS (CERN). Предложен эффективный способ увеличения ресурса калориметров путем комбинации восстановления оптических свойств системы сцинтиллятор + световод и мер по уменьшению (смещению) максимальной величины дозы.

Работа выполнена в Лаборатории высоких энергий ОИЯИ.

1. Introduction

Performance of the experiments at the high energy beams of the high intensity accelerators like the LHC, RHIC, etc., puts strong requirements on the radiation resistance of the detectors being used. In this case the major loading corresponds to the forward calorimeters. Obviously, the simulation of radiation loading and the results of test experiments are very important for development of detectors. It has been commonly acknowledged the high reliability of FLUKA and MARS [1] as the radiation level estimators for the primary high energy protons. These codes have been successfully tested [2].

However, the corresponding experimental results are practically absent for the beams of high energy nuclei with the exception of data [3] obtained at the energies by 10 GeV/nucleon.

In this work, for the first time the absorbed doses in scintillators of hadronic calorimeter are measured and compared with the calculation results for the Pb-Pb interactions at 157.7 GeV/nucleon energy. For this purpose we have used the Zero Degree Hadronic Calorimeter (ZDC) of WA-98 experiment at CERN SPS. The ZDC is located at the far end of the set-up and sees in the forward direction of secondary particles and beam nuclei passing without interaction in a target.

2. Dose Simulation

The cascade, induced by heavy relativistic nucleus, has the new component which, in its turn, is the cascade of the multicharge fragments (MFC). In contrast to the proton-nucleus interactions, the nucleus-nucleus ones have additional sources of the nucleon-meson cascade (NMC) — nucleons of the spectator residuals of the primary nuclei and of the electron-photon shower (EPS) — photons, appeared due to the excitation removal of the largest fragments of these residuals.

Electrodissociation of the target nucleus gives the contribution to the dose for the proton-nucleus cascade at energies more than several hundred GeV. The electrodissociation cross section is already comparative with the one of other nuclear process of the nucleus-nucleus cascade (particularly, for Pb-Pb) at the energies of a few tens GeV/nucleon. Since the velocities of the hadrons and fragments, emitted by the primary nucleus, are approximately equal to the projectile ones, the electrodissociation process has to be

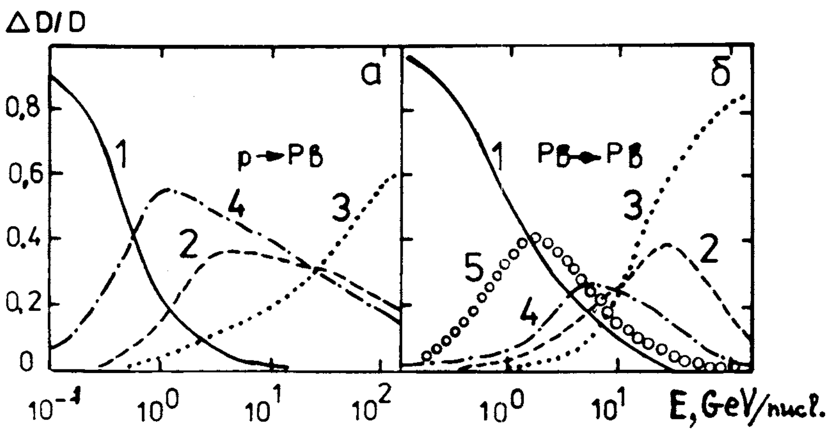
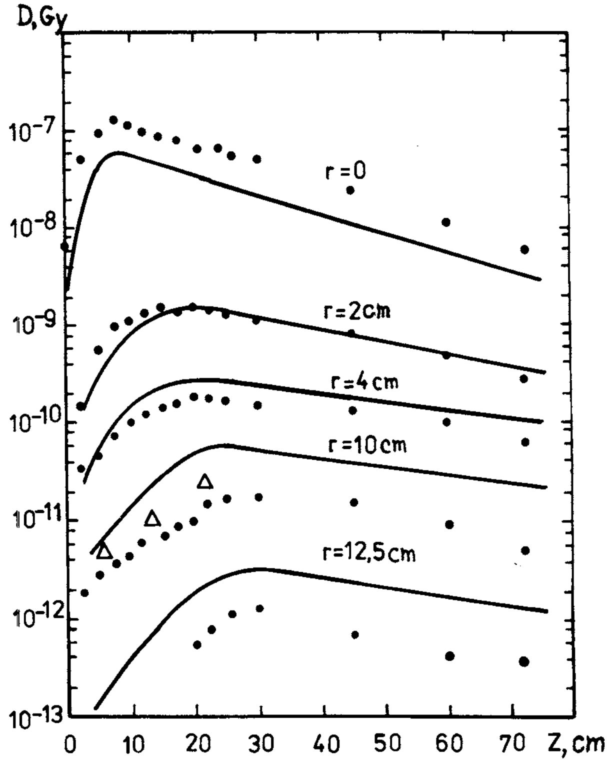


Fig.1. Contributions of the cascade components to the maximum dose in the semi-infinite lead block [3]: 1 — primary particles; 2 — nucleon-meson cascade; 3 — electron-photon shower; 4 — low energy charge particles and neutrons; 5 — multicharge particles

Fig.2. Longitudinal distribution of the absorbed dose per one incident particle in the semi-infinite lead block: ●— experiment at 300 GeV (protons) [2]; ▬ — calculation by MARS code at 150 GeV [5]; △ — experiment at 157.7 GeV/nucleon, normalized by $A_{Pb} = 208$ times (see the table)



considered as the additional contribution to the dose from new sources of the NMC and EPS, and the nucleus dissociation of the environment material — as the new source of the low energy component of the cascade.

Figure 1 shows the secondary radiation contributions to the absorbed dose (in cascade maximum) in dependence on the primary particle energy. The estimation is made with the EDMONT code [3], which has been preliminarily tested by means of comparison with experimental dose values, obtained by means of calorimetric dosimeters on the 2.55 GeV proton, 7.31 GeV/nucleon deuteron, 3.65 GeV/nucleon carbon nucleus beams of JINR's Synchrophasotron [4].

At the energies of a few hundred the dose is determined mostly by the EPS, induced by $\pi^0 \to \gamma\gamma$ decays, and therefore the radial distribution $D(r)$ in the cascade maximum coincides with the corresponding distribution of the electromagnetic shower [1,2].

The spatial dose distribution was calculated in the lead dump of the 150 GeV proton beam [5] with the use of the modified MARS code version [1]. In Fig.2, the longitudinal dose distribution is compared with the experimental one at 300 GeV [2]. As expected, the calculated curves underestimate the experimental points at $r = 0$, coincide with them at $r = 2$ cm and overestimate the measured values at $r = 12.5$ cm. Such a picture is explained by difference of the projectile proton energies. The radial dose distribution at $z = 17$ cm (Fig.3), obtained with the EDMONT code, demonstrates it.

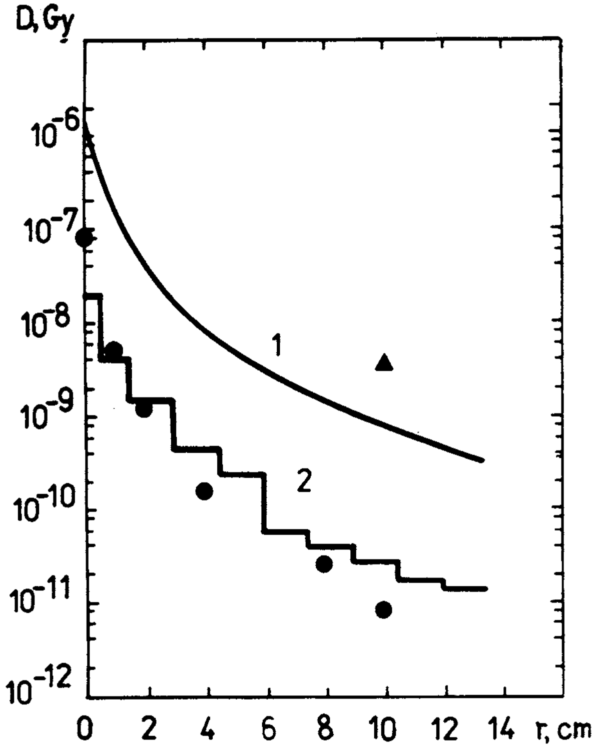


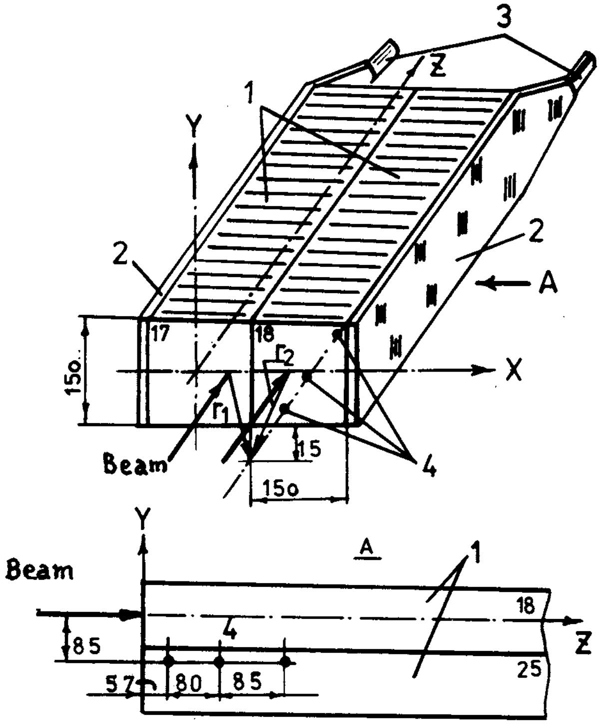
Fig.3. Radial distribution of the absorbed dose per one primary particle in the semi-infinite lead block at $z = 17$ cm: 1 — for 100 GeV/nucleon Pb nuclei, calculation by EDMONT code [3], experiment ▲ at 157.7 GeV/nucleon; 2 — for 150 GeV protons, calculation by MARS code [5], experiment ●at 300 GeV [2]

3. Absorbed Dose Measurements

The ZDC calorimeter has $75 \times 105 \times 1850$ cm^3 dimensions and consists of 35 modules *with 15×15 cm^2 cross sections. Every module represents a set of alternating plates of* scintillation material (PS) and lead one with thickness of 2.5 mm and 10 mm, respectively. Figure 4 shows the irradiation geometry for two central modules with wave length shifters (WLS). During the run the beam had two positions but that did not affect results ($r_1 = r_2$). In our experiment, very thin film dosimeters may be used only in order to place them into the splits between the modules avoiding the calorimeter demounting. We could place, as it is shown in Fig.4, three colour film CDP-4-1 dosimeters (analogous to the FWT-70 [6]), developed on the polychlorstyrene basis with 150 μm thickness, 1 cm^2 cross section and 1.2 g $\cdot$ cm^{-3} density. These detectors are able to measure the absorbed dose in the interval from 10 to $2 \cdot 10^2$ Gy.

CDP-4-1 detectors considerably differ from other film detectors in several important characteristics. They have not any detectable postirradiation effect and are slightly sensible to oxygen. The detector readings do not depend on the dose rate over the range $10^{-4} \div 10^2$ Gy $\cdot$ s^{-1} at the room temperature. At the temperature raise up to 70°C, the film dosimeter readings change by three times. Because of small dimensions and the radiation

Fig.4. Irradiation geometry of the central modules (the rest modules are not shown): 1 — alternating scintillation and lead plates; 2 — wave length shifters; 3 — photoelectric multipliers; 4 — CDP-4-1 film dosimeters



similarity, the detector location between the calorimeter modules does not distort the secondary radiation field. Under irradiation, the film dosimeters are getting the specific color in the dependence of the absorbed dose value. Detailed investigations of these dosimeters are performed in the work [6]. Dose values are obtained from the optical density measured by the SF-26 photospectrometer and graduation curves.

While being calibrated with the ^{60}Co-source ($\bar{E}_\gamma \sim 1.25$ MeV), our dosimeters were placed in the material, which was equivalent to the detector one in order to obtain the electron equilibrium. The total error did not exceed 12% at the confidence interval of 0.95. For the first time we performed the calibration of the colour film dosimeters in complex radiation field of the nuclear-electromagnetic cascade at the energies from several units to tens GeV. The above-mentioned copper microcalorimeters [4] were used as the test dosimeters. In this case the uncertainty was estimated to be as high as 25% due to the experimental inaccuracy and the imperfect radiation similarity.

To obtain the equivalent effect (optical density) the larger absorbed dose is necessary in complex field than in the case of γ-irradiation. It is seen, that for higher energies of projectile particles this difference decreases since the linear transmission of the energy (LTE) decreases also with the growth of contribution of the electron-photon shower to the total dose (see Fig.1).

The experimental results of the absorbed dose measurements are presented in the Table.

Table. Experimental results for Pb-Pb interactions with 157.7 GeV/nucleon energy

Seance	Number of Pb nuclei during one run	Time of the irradiation, s	Beam size, mm	Dose (Gy) in points with coordinates (cm)		
				$r = 10$, $z = 5.7$	$r = 10$, $z = 13.7$	$r = 10$, $z = 22.2$
November — December, 1995	$\sim 10^{11}$	$3 \cdot 10^{6}$	$\sigma_x = 4$, $\sigma_y = 5$	118 ± 30	220 ± 55	522 ± 13

4. Discussion

It is necessary to stress that the dose from the hadrons is several times higher than that one from γ-radiation (^{60}Co) with the equal optical density of polystyrene [6], that is also confirmed by our dosimeter calibrations.

From the other hand, the permissible limit dose $D_{\lim}$ of the PS + WLS system in hadron field of the operating calorimeter is, in contrast, less than one in the isotope source tests [7,8]. Authors of [8] tried to explain the 10-times discrepancy of the prediction and results by accounting for the considerable difference of dose rates, which were equal to $2.8 \cdot 10^{-5}$ $Gy \cdot s^{-1}$ (^{60}Co) and $5.6 \cdot 10^{-7}$ $Gy \cdot s^{-1}$ (hadrons), when radiation oxidation effects appeared.

Rough estimations showed [9], that the dose in scintillator was $D_{PS} = 4.3 \cdot 10^{3}$ Gy and that one in the wave length shifter closest to the particle beam (Fig.4) was $D_{WLS} = 36$ Gy, where the dose rate was in the interval $10^{-2} \div 10^{-4}$ $Gy \cdot s^{-1}$. Light losses of scintillator samples were 10% at $D_{\lim} = 5 \cdot 10^{4}$ Gy and at the dose rate of 2.8 $Gy \cdot s^{-1}$.

However, the radiation oxidation effect was not observed under irradiation by ^{60}Co source with dose rates $6 \cdot 10^{-2}$ $Gy \cdot s^{-1}$ and $3.2 \cdot 10^{-3}$ $Gy \cdot s^{-1}$ [10]. Therefore we believe that the type and energy of secondary particles, operation conditions (temperature, joint affection of radiation and light) are also important and can lead to the opposite result. The light intensity in the maximum of the cascade curve for the ZDC is $\sim 10^{15}$ $cm^{-2} \cdot s^{-1}$.

The photoradiation affection is the complex process and cannot be considered as the direct sum of radiation and light affections. The photoradiation growth of outputs of intermediate active particles and the polymer destruction can overcome the recombination of particles or the destruction decrease with the LET increase of irradiating particles without the light affection ($LET_{\gamma} \sim 0.2$ keV/μm; $LET_{hadrons} \sim 20$ keV/μm).

The relaxation of intermediate active particles [11] slows down due to the photoradiation. The optical properties recover faster with the LET increase under irradiation without light. Moreover, under the affection of the photoradiation the efficiency of scintillation, spectrum displacement and antiradiation ingredients shows down also. So, radiation-resistant scintillators can have the smaller photoradiation resistance than that one predicted from simple radiation tests [12,13].

5. Conclusion

The problem of correspondence of the permissible limit dose obtained by isotope source tests, to the real $D_{\lim}$ values for calorimeters is related to the correct determination of spatial dose distributions in both scintillators and wave length shifters. To solve this problem it is necessary to perform the benchmark experiment on a model of working calorimeter with the correct mathematical simulation of particle transport over the energy range from several hundred GeV to tens TeV.

At the real calorimeter exploitation the dose collection will be accompanied by the periodical interruptions. Therefore the recovery of the optical properties of the PS + WLS system by means of interruption (relaxation) combinations and very small displacements of the beam meeting point is perspective way to increase the calorimeter resource.

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