STATE RESEARCH CENTER OF RUSSIA

INSTITUTE FOR HIGH ENERGY PHYSICS

IHEP 2002–12

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IONIZATION SPECTRA FROM NEUTRON BACKGROUND IN THE MUON CHAMBERS ON THE CMS

Submitted to *NIM*

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Protvino 2002

UDK 539.12.173 M–24

Abstract

Sannikov A.V., Uzunian A.V. Ionization spectra from neutron background in the muon chambers on the CMS: IHEP Preprint 2002–12. – Protvino, 2002. – p. 8, figs. 7, tables 2, refs.: 11.

The ionization spectra in the ME1/1 chamber from heavy charged particles produced by neutron background have been calculated by the HADRON code. Two problems associated with these background events are considered – decrease of the chamber efficiency and possible destruction of readout channels due to high local ionizations. The second problem was found to be potentially important that requires to study the possible ways of the chamber protection. Similar problems can take place for other ionization chambers at the collider experiments.

Аннотация

Санников А.В., Узунян А.В. Спектры ионизации от нейтронного фона в мюонных камерах на CMS: Препринт ИФВЭ 2002–12. – Протвино, 2002. – 8 с., 7 рис., 2 табл., библиогр.: 11.

Спектры ионизации в камере ME1/1 от тяжелых заряженных частиц, образованных фоновыми нейтронами, рассчитаны по программе HADRON. Рассматриваются две проблемы, связанные с этими фоновыми событиями, – снижение эффективности камеры и возможное повреждение считывающих каналов из-за ионизаций с высокой плотностью. Подобные проблемы могут иметь место для других ионизационных камер на коллайдерных экспериментах.

Introduction

The ME1/1 muon chambers on the CMS experiment at LHC are awaited to operate in the conditions of very high neutron background ($\sim 10^{12}$ cm^{-2} ten year fluence) [1]. These neutrons produce a large number of charged secondaries in the chamber volume to be discriminated from muons. The problem of background discrimination is supposed to be solved by using six sensitive planes of the chamber working in coincidence. The main part of charged particle background will be rejected by this method resulting, however, in some decrease of the chamber efficiency.

The other problem of neutron background is associated with the relatively rare high local ionization events in the sensitive volumes which may cause the following negative effects:

- decrease of the chamber efficiency due to the long dead time and recovery time;
- transition of the chamber to the streamer or spark regime with possible burn out of the readout electronics or destruction of the anode wires [2].

To estimate the chamber efficiency, its tolerance to the background radiation and possible ways to protect the readout channels, event spectra from the neutron background have to be known.

The initial spectra of heavy charged particles produced by neutrons in the chamber gas were calculated previously. It was shown that the main contribution give He, C and O ions from elastic and inelastic neutron collisions with carbon and oxygen nuclei. The maximum energy deposition per wire for such events was estimated as 20 MeV approximately which is 4 orders of magnitude higher compared to the few keV deposited by high-energy muons. This work is devoted to calculation of the event spectra from the neutron background with a full geometry description of the ME1/1 chamber taking into account some factors not considered earlier: a) charged particle transport in magnetic field; b) contribution of walls and wires; c) contribution of low-energy neutrons. The final results are given in a scale of ionization energy deposition per wire proportional to the number of initial ion pairs liberated in a sensitive volume.

The event spectra presented in this paper include energy depositions from secondary charged particles heavier than muon. The energy spectra and fluences of light charged particles ($e^{\pm}, \mu$) have been calculated earlier [1] and are not considered here.

1. Model of calculation

1.1. Geometry

The ME1/1 chamber [3] consists of the six 7 mm thick sensitive gas layers with a gas composition of (50% CO_2 - 40% Ar - 10% CF_4) by volume and 0.0021 g/cm^3 density. Each plane contains 600 anode wires 50 cm long on average, positioned 2.5 mm from each other. It may be considered as a set of 600 sensitive volumes with average dimensions of 0.25x0.7x50 cm^3. In reality, the wire length increases in radial direction due to azimuthal symmetry of the chamber construction. The chamber walls are made from G10 0.8 mm thick laminated by 18 μm Cu layer (cathode). The walls of neighbouring sensitive planes are separated by 1.44 cm thick honeycomb structure made from G10 as well. The full description of the ME1/1 geometry and environment is given in [3]. It was reproduced in calculations including the HE steel flange and aluminium support disk.

1.2. Source and types of secondary charged particles

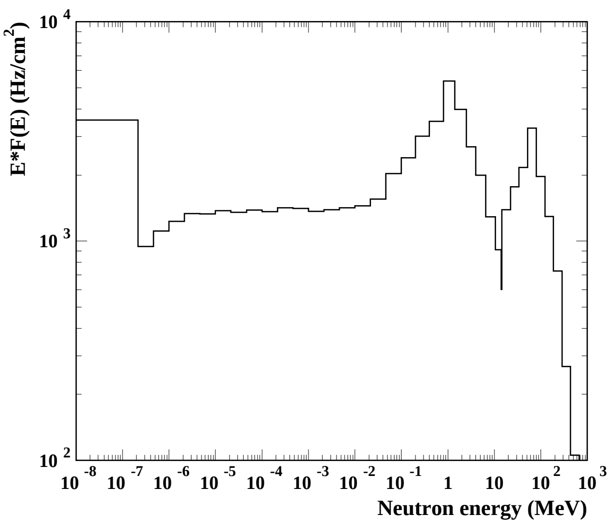

Fig. 1. Neutron energy spectrum in the ME1/1 chamber slot.

Calculations were made assuming an isotropic irradiation of the chamber gas, walls and environment by the neutron spectrum calculated by MARS [4] for the conditions of full LHC luminosity (10^{34} Hz/cm^2). The neutron energy distribution at the centre of chamber (R = 180 cm) is shown in Fig. 1. The spectrum above 100 keV is characterised by the evaporation and cascade peaks at neutron energies of 1 MeV and some tens of MeV, correspondingly. Below some MeV, neutrons produce only low-energy elastic recoils in the chamber gas and walls. The high-energy cascade peak of the neutron spectrum is much more important as a source of secondary heavy charged particles which may be divided into the following main groups:

- high-energy protons and pions produced mainly in the chamber walls and environment;
- elastic and inelastic recoils from neutron interactions with gas nuclei;
- light complex particles (d, t, ^{3}He, α);
- fission fragments emitted from wires.

Stopping powers and ranges of some ion species in the chamber gas calculated by the TRIM code [5] are presented in Fig. 2. The electronic (ionizing) part of the total stopping power responsible for creation of ion pairs in the gas is also shown. One can see that the maximum values of ionization energy loss reach up to $\sim$1, 3, 20 and 100 MeV/cm for ^{1}H, ^{4}He, ^{16}O and ^{88}Sr ions, respectively. On the other hand, the right part of Fig. 2 shows that the considered ions with kinetic energies of 1.1, 4.2, 30 and 120 MeV are fully absorbed in 2 cm of the chamber gas. These values roughly define the range of ionization events for different ions. It should be also noted that considerable part of heavy charged particles is produced in inelastic collisions with multiple fragment emission. The most important of them are ^{12}C$(n,n')3\alpha$ and ^{16}O$(n,n')4\alpha$ with high enough cross sections in the neutron energy range of interest. Another important channel providing extremely high local ionizations is fission events in the anode wires.

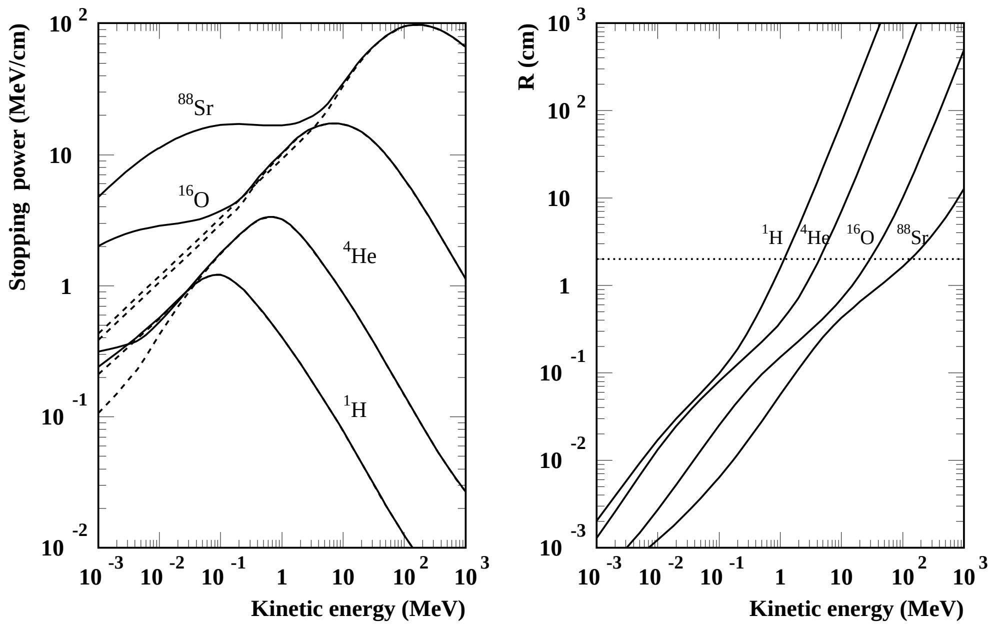

Fig. 2. Stopping powers (left) and ranges (right) of some ions in the ME1/1 gas. Dashed curves on the left figure represent the ionizing component of the total stopping power.

1.3. Generation of charged particles

Calculations were made using the high-energy transport code HADRON [6] based on the cascade-exciton model of nuclear reactions. Its essential feature is an accurate physics of nucleon-induced reactions below 100 MeV where all the models have serious problems. Cascade stage of a nuclear reaction is calculated taking into account refraction of particles by the mean-field nuclear potential. This potential is described by the real part of an optical potential whereas its imaginary part is used for the simulation of cascade particles absorption. The process of nucleus deexcitation after the cascade stage is considered in frame of preequilibrium exciton model including an equilibrium approach as a final stage.

The model is essentially based on the experimental data on nuclear properties. This is related to the cross sections, used at the cascade and deexcitation stages, nuclear level densities including shell and pairing effects etc. Binding energies of emitted particles are calculated at all stages from a database of experimental nuclear masses. The discrete structure of low-lying nuclear excited states is explicitly taken into account. This is especially important for light even-even nuclei where energy of the first excited state may amount up to some MeV (4.44 MeV for ^{12}C and 6.05 MeV for ^{16}O). The most recent version of HADRON includes the coalescence and pickup models of fast complex particle emission (d, t, ^{3}He, α) at the cascade and preequilibrium stages, correspondingly.

Inelastic collisions with chamber nuclei were simulated by HADRON at all neutron energies above the thresholds. The total inelastic and elastic cross sections above 20 MeV are calculated in HADRON using parametrisation [7]. For simulation of elastic scattering at $E_n > 20$ MeV, the modified Ranft formula [8], adjusted to experimental data for light nuclei, is used. The total cross sections and elastic recoil energy spectra for low-energy neutrons were generated from the ENDF/B-VI library [9]. Only neutron interactions with gas nuclei were taken into account in this case due to short ranges of charged secondaries.

Anode wires are made from tungsten ⊘ 30 μm coated by gold (5% of the total wire mass). The ^{197}Au and ^{184}W nuclides are fissionable by high-energy neutrons. For description of fission process, we have used a simple semi-empirical model based mainly on the experimental and theoretical proton fission data from [10]. The reason for such a choice is that the neutron fission data are very scarce whereas theoretical models are not reliable for the considered nuclides.

The effective fission cross sections for our neutron spectrum above the fission threshold (~100 MeV) have been estimated as 22 mb for ^{197}Au and 1.2 mb for ^{184}W. Mass distributions of fission fragments were sampled from gaussians with $\bar{A}$ =(88, 83) and σ_A =(13.2, 12.0) parameters. The corresponding fragment charges were taken at the line of β-stability. The total kinetic energy of fission fragments was estimated from systematics:

$$\bar{T}_\Sigma = 0.121 \cdot Z_M^2 / A_M^{1/3} \tag{1}$$

where Z_M, A_M - charge and mass of target nucleus. The values of $\bar{T}_\Sigma$ for ^{197}Au and ^{184}W are equal to 130 and 116.5 MeV. Distribution of $\bar{T}_\Sigma$ between two fragments and their directions of fly were calculated in the assumption of $\vec{P}_1 + \vec{P}_2 = 0$ in the CM system. Fission fragments were assumed to be accompanied by one proton and one α-particle [10].

1.4. Calculation of event spectra

The models of fission fragments and low-energy neutron recoils production were introduced into the HADRON code to describe transport of secondary charged particles from different sources in a unique way. For the considered internal neutron source, the total number of neutron collisions with chamber nuclei at radius R is defined by

$$N_{col}(R) = \sum_i V_i \int \Phi(E_n, R) \Sigma_i(E_n) \mathrm{d}E_n, \tag{2}$$

where $\Phi(E_n, R)$ is the neutron spectrum at radius R; V_i — volumes of the chamber parts (walls, gas, wires etc.); Σ_i — total macroscopic cross sections for the corresponding media. This expression was a basic one for sampling the relative probabilities of neutron collision in different volumes and for normalising final results.

Particle transport is simulated in HADRON in frame of the well-known step method in which particle trajectory is divided into small segments to take into account such physical processes as multiple scattering, energy loss straggling etc. Charged particle deviation in a magnetic field is easily calculated as well in this approach. For this purpose, formulations [11] were used. Magnetic field with a flux density of 3 T was taken to be normally directed to the chamber planes.

For each part of the chamber (walls, gas and wires), 10^6 neutron interactions with nuclei were simulated to provide good statistics in different regions of the event spectrum. The scoring procedure included calculation of total ionization energy deposited by all secondary charged particles from each neutron collision in different sensitive volumes. The term "ionization energy" means that only ionising part of the total stopping power was included in energy deposition (see Fig. 2). This approach effectively takes into account energy dependence of W (average energy required for creation of an ion pair).

2. Results and discussion

The radial event rate distribution is shown in Fig. 3 together with the neutron fluence rate data [1] used in our calculations. One can see that the neutron fluence has a strong radial gradient. The corresponding event rate dependence is expressed somewhat less due to increasing the length of wires in radial direction. To eliminate the radial dependence of event spectra, the presented below results are given for the central part of the chamber ($\bar{R} = 180$ cm) and obtained by averaging over 200 wires. Fig. 4 demonstrates the event rate distribution in dependence on the number of simultaneously ionised sensitive volumes. The main part of neutron interactions leads to small number of hit wires (< 10) due to production of short-range charged particles or due to geometry factor in case of high-energy particles. The tail of event rate distribution has an exponential shape and extends up to 100 wires and more.

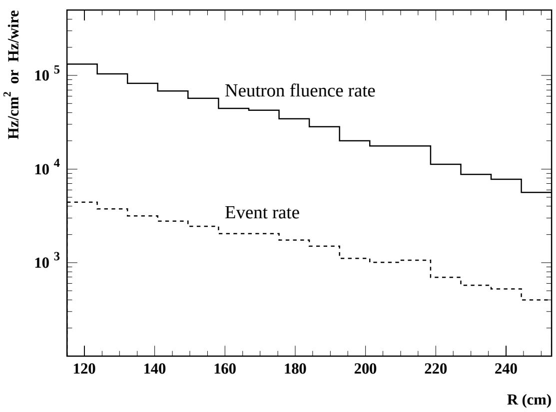

Fig. 3. Radial distributions of neutron fluence rate and event rate in the ME1/1 chamber.

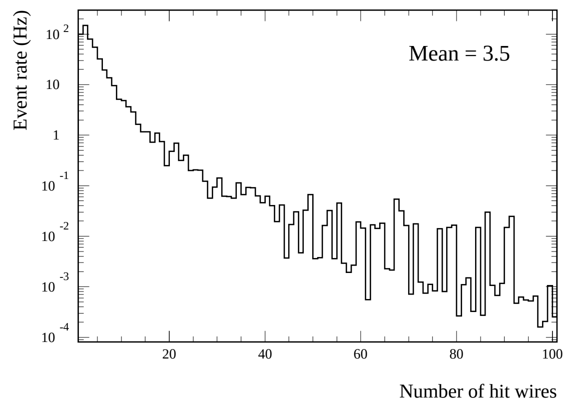

Fig. 4. Event rate distribution on the number of simultaneously hit wires.

The total event spectrum and contributions of walls (including environment), gas and wires are presented in Fig. 5. The spectra are given in a scale of $\mathrm{d}\dot{N}/\mathrm{d}(\ln E_{ion})$ that is each bin of histogram represents the event rate per unit logarithm of ionization energy. The scale of ionization energy can be easily transformed into the number of ion pairs using the value of W=25 eV per ion pair accepted for the ME1/1 gas.

The main part of events is produced by high-energy long-range protons and pions emitted from the chamber walls. This component peaking at some keV is important for the problems of background discrimination and chamber efficiency. As regards high ionizations, the region of 1-20 MeV is dominated by charged particles from gas nuclei whereas extremely high local ionization events above 20 MeV are only produced by particles emitted from wires.

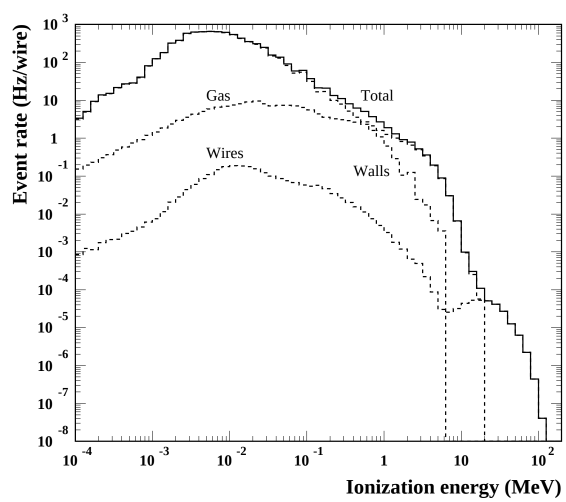

Fig. 5. Total event spectrum and its components at the center of chamber.

The partial contributions of different physical processes in the chamber gas and wires are shown in Fig. 6. One can see that recoils from low-energy neutrons do not contribute noticeably in the important region above 1 MeV. The same conclusion can be made about charged particles produced in wires in non-fission processes. The event spectrum from wires above 20 MeV, where this component is essential, is fully defined by the fission channel. These high ionization events are created mainly by fission fragments emitted from the gold layer. The tungsten contribution above 20 MeV is less than 10% due to much lower fission cross section and absorption of short-range fission fragments in wires.

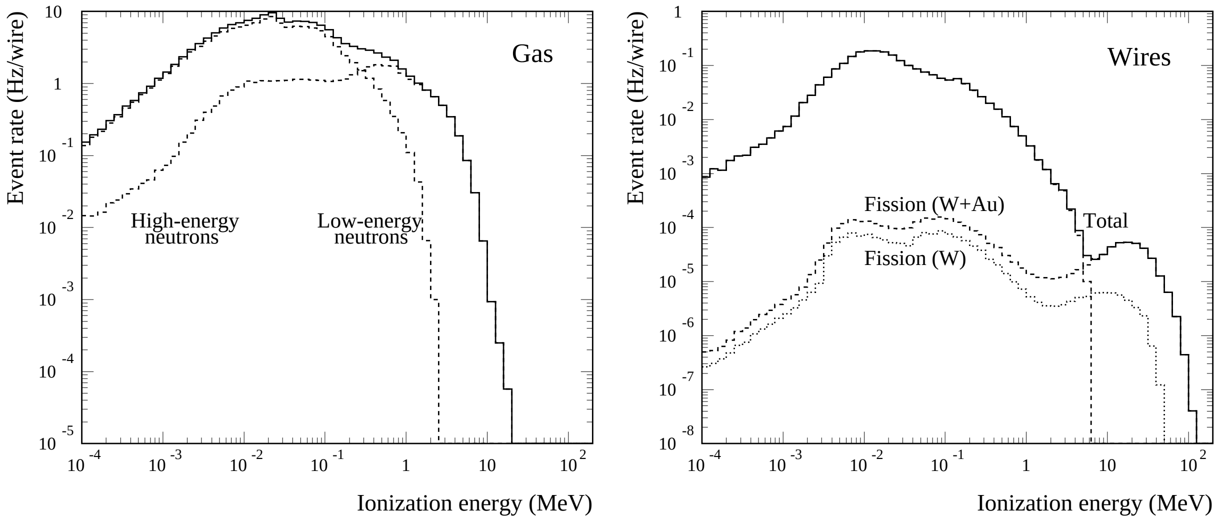

Fig. 6. Event spectra from charged particles produced in gas and wires.

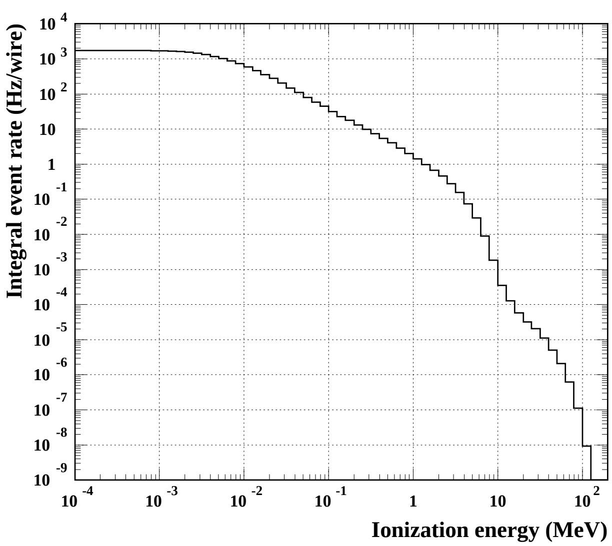

Fig. 7. Integral event rate at the centre of chamber.

The expected uncertainties of the calculated total event spectrum are defined as follows. Assuming the above considerations, the spectrum region below 20 MeV originates mainly from elastic and inelastic interactions of high-energy neutrons (cascade peak of the neutron spectrum). The accuracy of HADRON calculations is estimated in this case as better than 50% for all important components of the event spectrum. Above ionization energy of 20 MeV, where only fission channel contributes to the total spectrum, possible systematical error reach up a factor of 2-3. The main source of this uncertainty is due to the use of proton fission cross sections instead of neutron ones. It should be noted, however, that the uncertainty of input data have the same order of magnitude – the neutron spectra calculated by MARS and FLUKA differ up to 3 times from each other [1].

In Fig. 7, the integral event spectrum is shown for reader convenience. In this presentation, each bin gives the total rate of events above the corresponding ionization energy. These data are also presented in Table 1 for some values of E_{ion}. In the same Table, the integral event rates for the whole chamber, including 3600 wires in 6 planes, are given. The corresponding total event numbers for planning ten years of work (assuming 180 working days per year) are presented in Table 2. These results clearly indicate that even highest possible ionization energy events with E_{ion} >100 MeV can not be neglected since the most part of wires (or readout channels) may be destroyed due to such events during the working time of the ME1/1 chamber.

Table 1. Integral event rates above the ionization energies E_{ion}.

E_{ion}(MeV)	10^{-4}	10^{-2}	0.1	1	10	100
$\dot{N}^{>E_{ion}}$(Hz/wire)	$1.74 \cdot 10^3$	$5.83 \cdot 10^2$	$3.12 \cdot 10^1$	$1.40 \cdot 10^0$	$3.54 \cdot 10^{-4}$	$9.35 \cdot 10^{-9}$
$\dot{N}_{tot}^{>E_{ion}}$(Hz)	$6.89 \cdot 10^6$	$2.31 \cdot 10^6$	$1.24 \cdot 10^5$	$5.54 \cdot 10^3$	$1.40 \cdot 10^0$	$3.70 \cdot 10^{-5}$

Table 2. Integral event numbers above the ionization energies E_{ion}.

E_{ion}(MeV)	10^{-4}	10^{-2}	0.1	1	10	100
$N^{>E_{ion}}$(event/wire)	$2.70 \cdot 10^{11}$	$9.07 \cdot 10^{10}$	$4.87 \cdot 10^9$	$2.17 \cdot 10^8$	$5.51 \cdot 10^4$	$1.45 \cdot 10^0$
$N_{tot}^{>E_{ion}}$(event)	$1.07 \cdot 10^{15}$	$3.59 \cdot 10^{14}$	$1.93 \cdot 10^{13}$	$8.61 \cdot 10^{11}$	$2.18 \cdot 10^8$	$5.75 \cdot 10^3$

3. Summary and conclusions

The calculated total ionization event spectrum shows that the main part of events is produced by high-energy protons and pions emitted from the chamber walls. The total event rate is equal to 1740 Hz/wire. This value should be compared with the muon and electron backgrounds for which only fluence rates were calculated [4]. In case of muons, this estimate can be made in an assumption of normal exposure of the chamber planes that is enough realistic. Each muon hits in this situation only one wire providing the scaling factor from fluence rate to event rate equal to the square of sensitive volume: 0.25x50 cm^2/wire = 12.5 (Hz/wire)/(Hz/cm^2).

For the main background charged particles - electrons - this scaling can not be easily obtained due to their wide spectrum, isotropic source and strong influence of the magnetic field, that requires to perform additional calculations. One more factor to be taken into account in the analysis of the chamber efficiency and of the relative contributions of different background components is the dead time and recovery time roughly proportional to the pulse amplitude. This factor will strongly enhance the relative importance of heavy charged particles compared to light ones (e, μ).

The problem of high ionization events and of their influence to the readout channels requires to perform experimental studies. In our calculations, we did not consider some physical effects which may strongly decrease the effective charge collected on wires in case of high local ionizations. As was stated above, the calculated event spectrum is nearly fully produced by the cascade peak of the neutron spectrum. Its shape is enough representative and can be simulated outside shields irradiated by high-energy hadrons above some hundreds of MeV. Another possible way is the use of the PSI standard test irradiation facility (300 MeV protons). From our estimate, this test would be good enough for the event spectrum region of high ionizations.

The main result to be obtained in the experiment is the possibility of the readout channels destruction and the probability of such events. After such studies, it will be also possible to compare the experimental event spectra with the calculated ionization spectra to answer the question about the efficiency of charge collection depending on primary ionization. If the problem will be found to be important, the methods of the chamber protection and the ways of background decrease are to be considered. One possible way of strong suppression of very high fission ionization events is seen from our results. It consists in the substitution of the gold wire coating by lighter metal if this is possible from performance requirements.

We would like to thank A. Zarubin, S. Movchan, P. Moissenz, V. Perelygin and M. Huhtinen for fruitful discussion of the considered problems.

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Received April 4, 2002

Препринт отпечатан с оригинала-макета, подготовленного авторами.

А.В. Санников, А.В. Узунян
Спектры ионизации от нейтронного фона в мюонных камерах на CMS.

Оригинал-макет подготовлен с помощью системы LaTeX.

Подписано к печати 09.04.2002. Формат 60 × 84/8.
Офсетная печать. Печ.л. 1. Уч.-изд.л. 0.8. Тираж 160. Заказ 68.
Индекс 3649. ЛР №020498 17.04.97.

ГНЦ РФ Институт физики высоких энергий
142284, Протвино Московской обл.

Индекс 3649

П Р Е П Р И Н Т 2002–12, И Ф В Э, 2002