CHARACTERISTICS OF SLOW PARTICLES IN HADRON-NUCLEUS INTERACTIONS AND THEIR RELATION TO THE MODELS OF HIGH-ENERGY INTERACTIONS

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Some characteristics of grey and black tracks (treated separately) produced in the interactions of high-energy hadrons with nuclei were investigated. Differences in the behaviour of these two groups of particles were shown. It has been concluded that one can use the number of grey tracks N_g as the good measure of the number of collisions of the primary particles inside the nucleus. Furthermore we compared the experimental dependence of normalized multiplicity R on the mean number of collisions $\bar{\nu}$ with theoretical predictions in an interval of $\bar{\nu}$ about twice as large as was possible in previous experiments (namely up to $\bar{\nu} \approx 7$).

1. Introduction

From among many models of interactions of high-energy hadrons with nuclei we may distinguish the group of models in which hadron-nucleus interaction is interpreted as a sequence of approximately independent collisions (interactions) with single nucleons inside the nucleus. A review of these models may be found e.g. in the paper of Zalewski [1]. Authors of these models very often discuss the dependence of the mean normalized multiplicity $R = \langle n \rangle_A / \langle n \rangle_H (\langle n \rangle_A$ — average multiplicity in the interaction of hadron with the nucleus with mass number A, $\langle n \rangle_H$ — average multiplicity in hadron-proton interaction at the same energy) on the mean number of collisions $\bar{\nu}$ inside the nucleus. This dependence was investigated experimentally in many works (Florian et al. [2], Busza et al. [3], Babecki [4]).

In all experiments made to date the different values of $\bar{\nu}$ were realized by means of the use of targets with different A ($\bar{\nu}$ was evaluated by means of the well known formula $\bar{\nu} = A \frac{\sigma_{hp}}{\sigma_{hA}}$, where σ_{hp} and σ_{hA} are inelastic and incoherent cross-sections of hadrons for interactions with protons and nuclei with mass numbers A). Therefore $\bar{\nu}$ was limited to about 4 (it corresponds to the interactions p-U).

However, it is known from the theoretical calculations (Lebedev et al., Błeszyński, Otterlund [5]) that the probability distribution of the number of collisions $P(\nu)$ for the nucleus with fairly large A is very wide. E. g. for the interactions of protons with "mean"

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nucleus of emulsion ($\langle A \rangle \approx 70$) we have $P(1) = 0.37$, $P(\geq 7) = 0.06$ (see Fig. 4). Therefore we tried to find the experimental parameter which permits the division of experimental data obtained with one target into groups with different $\bar{\nu}$. In our opinion the number of so-called grey tracks N_g (most of them belong to protons with the kinetic energy from 30 to 380 MeV) can be used as such a parameter. In other words N_g can be treated as a good measure of the number of collisions. Using N_g as a measure of the number of collisions we could study the R vs $\bar{\nu}$ dependence for interactions of 200 GeV protons with nuclei of emulsion at a much larger interval of $\bar{\nu}$ (up to ~7) and compare this dependence with predictions of some models of independent collisions.

2. *The distributions of the number of grey and black tracks*

The tracks of slow (i. e. with the velocity $\beta < 0.7$) particles produced in high-energy interactions of primary particles with nuclei are generally divided into black tracks (with the range $R \leq 3600\ \mu$) and grey ($R > 3600\ \mu$ and relative ionization $g^* > 1.4$). The black

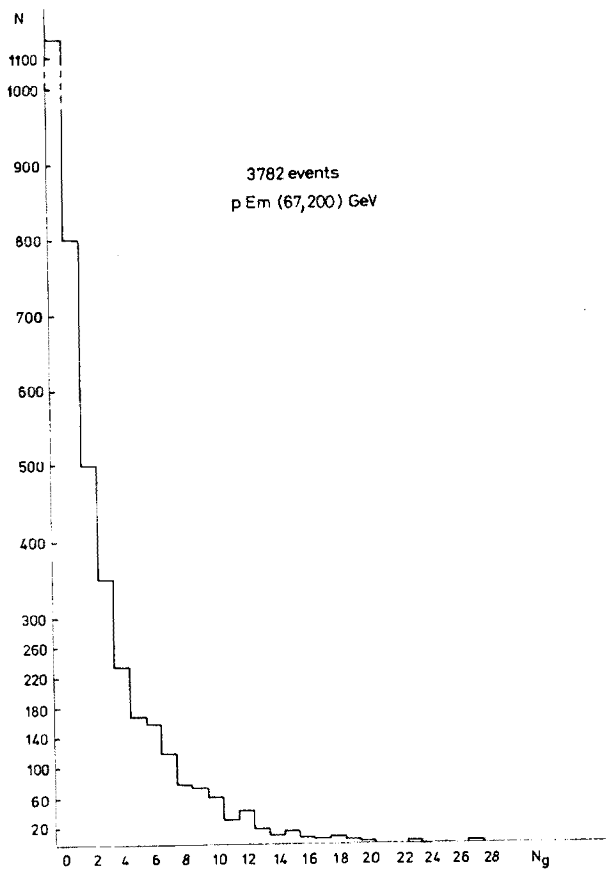

Fig. 1. The distribution of N_g for pEm interactions

tracks are usually considered as the products of evaporation of the nucleus and only a few of them can belong to recoil protons. Grey tracks belong mostly to protons with a small admixture of pions, deuterons and tritons, (see e. g. [6, 11]).

In Figs 1 and 2 the distributions of the number of grey tracks N_g and black tracks N_b in pEm interactions at the energies of 67 and 200 GeV are shown. Experimental data

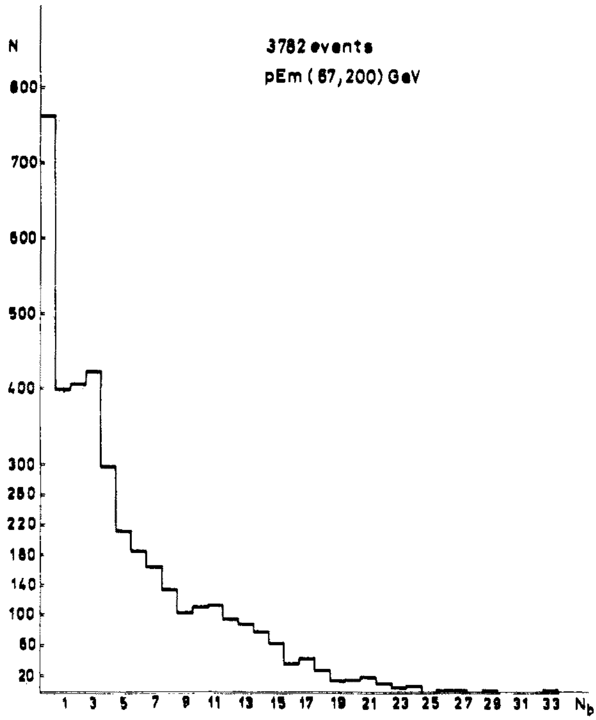

Fig. 2. The distribution of N_b for pEm interactions

at both energies come from Tashkent and Cracow laboratories. It is seen that N_g distribution and N_b distribution are different. Statistical analysis showed that N_g distributions as well as N_b distributions are the same at both primary energies.

In Fig. 3 the distributions of N_g and N_b for primary protons and pions are compared. Data for πEm interactions come from Chandigarh (17 GeV) and Cracow (60 and 200 GeV) laboratories. The appropriate distributions for πEm interactions are also independent of the primary energy.

The χ^2-test shows that N_b distributions are the same in the limits of statistical errors for both primary particles. The N_g distributions are different for primary protons and pions on the level of confidence $P(\chi^2) < 0.0005$. All experimental points belonging to pions for $N_g > 1$ lie below the N_g distribution for protons, whereas the points belonging to pions for $N_g = 0$ and 1 lie above the N_g distribution for protons.

In Fig. 4 one can see that the curve of N_g distribution for pions in comparison with N_g distribution for protons is similar to the curve of the distribution of probability $P(\nu)$

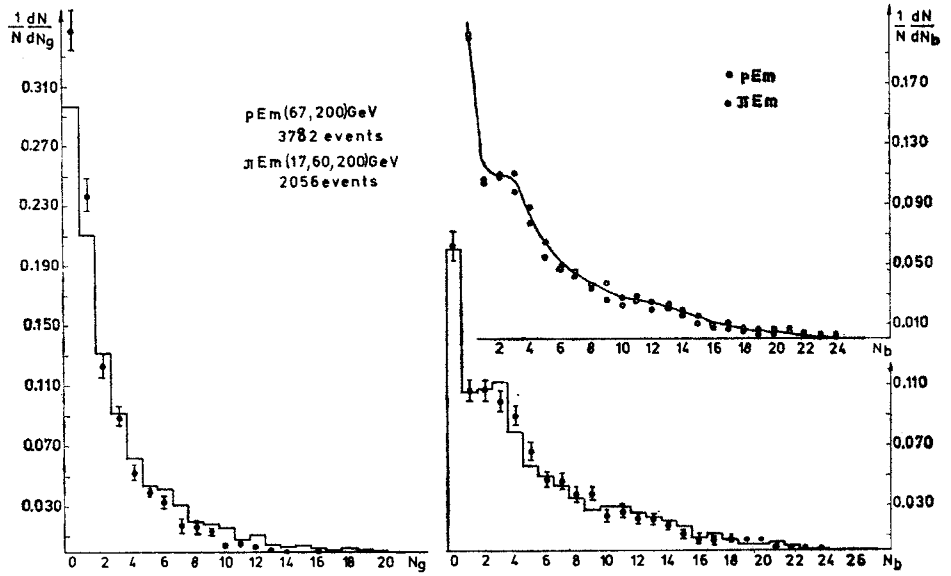

Fig. 3. The comparison of N_g distributions and N_b distributions for pEm and πEm interactions. The common solid line of N_b distribution for pEm and πEm together is drawn to guide the eye only

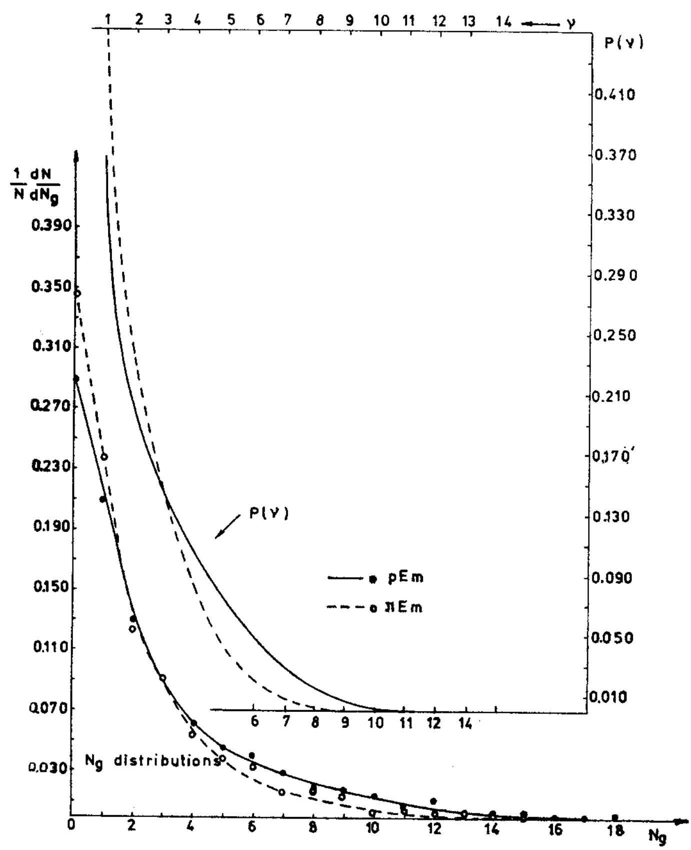

Fig. 4. The comparison of N_g distributions and $P(\nu)$ distributions for pEm and πEm interactions

for πEm interactions in comparison with $P(\nu)$ distribution for pEm interactions. The curves $P(\nu)$ are drawn on the basis of calculations of Błeszyński and those of Otterlund [5].

On the basis of the above mentioned comparisons we suppose that the number of grey tracks N_g may be treated as the experimental parameter which well represents the number of collisions.

3. The mean numbers of slow particles

In Fig. 5 the mean values $\langle N_g \rangle$, $\langle N_b \rangle$ and also $\langle N_h \rangle$ ($N_h = N_g + N_b$) for interactions of protons and pions with emulsion at different primary energies E_0 are presented. The experimental points come from the works [9, 20, 21] and also from many works cited in [15].

In a large interval of primary energy ($17 \lesssim E_0 \lesssim 2000$ GeV) $\langle N_g \rangle$, $\langle N_b \rangle$ and $\langle N_h \rangle$ do not depend on E_0 for a given primary particle (it was already shown for primary protons

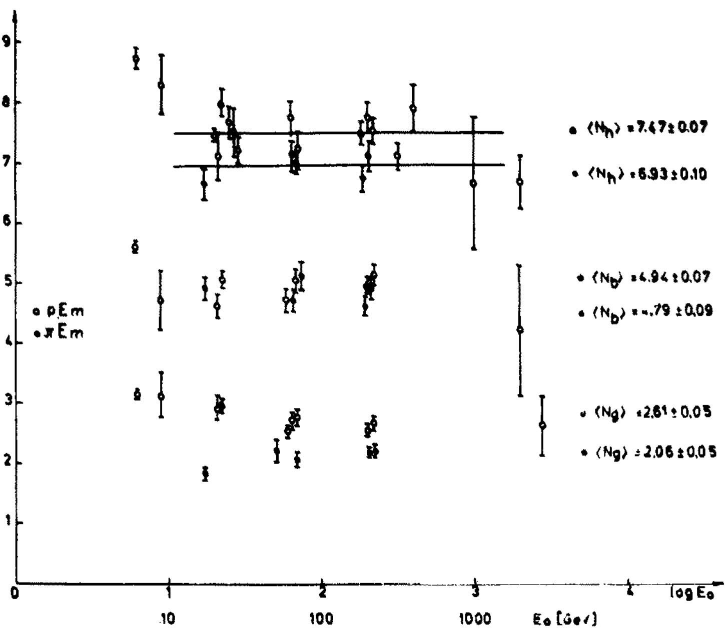

Fig. 5. The mean values of N_g, N_b and N_h at different primary energies for pEm and πEm interactions

[10, 13]). One can see also in Fig. 5 that $\langle N_b \rangle$ are the same in the limit of errors for primary protons and pions, whereas $\langle N_g \rangle$ for protons is distinctly larger than that for pions. Therefore also $\langle N_h \rangle_p$ is larger than $\langle N_h \rangle_\pi$, which was already shown in the work [20] for smaller samples of jets.

Mean values calculated by us for all available data in the above mentioned interval of primary energy are: $\langle N_b \rangle_p = 4.94 \pm 0.07$, $\langle N_b \rangle_\pi = 4.79 \pm 0.09$, $\langle N_g \rangle_p = 2.61 \pm 0.05$, $\langle N_g \rangle_\pi = 2.06 \pm 0.05$. These values support our belief that the number of grey tracks well represents the number of collisions, because it is known that $\bar{\nu}_p > \bar{\nu}_\pi$ [3–5].

4. *Recoil protons among grey and black tracks*

Calucci et al. [7] calculated on the basis of the data from bubble chambers at several hundreds of GeV and from ISR that the mean number of slow protons with the kinetic energy $\leqslant$ 380 MeV (i. e. grey and black tracks) in one pp interactions is $\sim$ 0.48.

We performed kinematical calculations assuming the rectangular distribution of the inelasticity in CM-system for pp interaction (this assumption seems rather reasonable [8]) and also two from among transverse momentum distributions which are often used: $dn = ap_\perp e^{-bp_\perp} dp_\perp$ and $dn = \alpha p_\perp e^{-\beta p_\perp^2} dp_\perp$ with $\langle p_\perp \rangle = 0.4$ GeV/c. By means of these calculations we obtained a weak dependence of the number of recoil protons with the energy $\leqslant$ 380 MeV on the primary energy in pp interactions: from 0.53 at $E_0 = 50$ GeV to 0.46 at $E_0 = 10\,000$ GeV. This numbers are in very good agreement with the results of Calucci et al.

By means of the same calculations we found that the number of recoil protons with the kinetic energy $\leqslant$ 30 MeV (black tracks) in one pp interaction is only $\sim$ 0.05 in the wide interval of primary energy from 20 to 10 000 GeV. Knowing the mean number of black tracks $\langle N_b \rangle$ in one jet and the mean number of collisions in the nucleus of emulsion we could evaluate that only $\sim$ 1% of black tracks can belong to the recoil protons.

On the other hand the contribution of recoil protons with the kinetic energy $30 < E_k \leqslant 380$ MeV to the grey tracks is much larger, namely $\sim$ 21% at the primary energies from 20 to 2000 GeV.

The existence of a large number of recoil protons among the grey tracks explains why N_g is a good measure of the number of collisions inside the nucleus.

It is worth noticing that although the group of grey tracks is enriched in recoil protons which could be produced in the interactions of primary particles with the nucleons inside the nucleus, the total number of protons among the grey tracks is much larger, namely (70–80) % (see e. g. [6, 11]). Hence, one can suppose that (50–60) % of grey tracks belong to protons produced in the secondary processes in the nucleus, probably in the elastic (rarely inelastic) scattering of recoil protons on the protons of the nucleus[1].

5. *The dependence of $\langle N_g \rangle$ on the multiplicity of secondary relativistic particles*

The multiplicity of secondary relativistic ($\beta > 0.7$) particles is certainly connected with the number of collisions inside the nucleus. Therefore the investigation of the dependence of various characteristics of grey tracks on the multiplicity may lead to finding the relation of the number of grey tracks and the number of collisions.

In Fig. 6 the dependence of $\langle N_g \rangle$ on R_2 i. e. the normalized multiplicity of particles "created" in the interactions of proton with the nucleus of emulsion is presented. $R_2 = n_2/(\langle n \rangle_H - 2)$, where n_2 means the multiplicity of charged particles minus the average number of charged particles which participated in interaction. It was shown in [4] that R_2 does not depend on the primary energy and therefore we could gather together experimental data at 67 and 200 GeV.

[1] The existence of elastic scattering of protons with the energies of hundreds of MeV in interactions of high energy particles with emulsion nuclei was observed in the work [11].

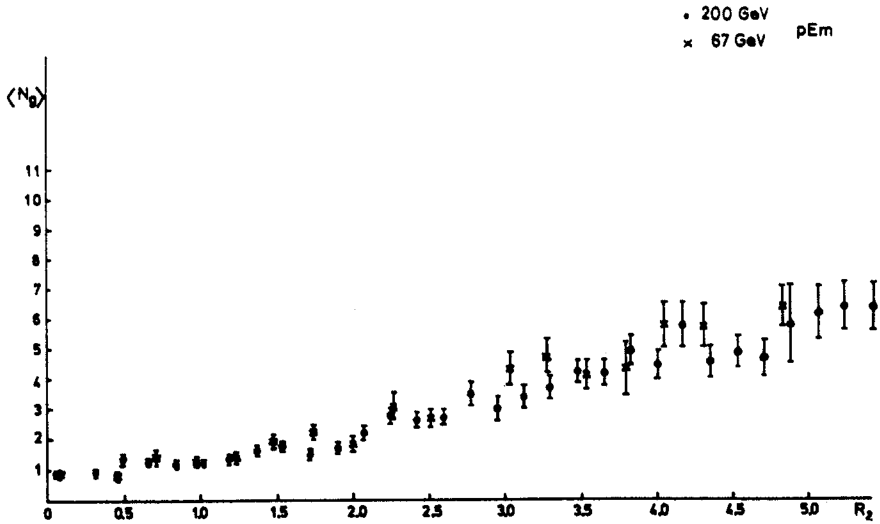

Fig. 6. The $\langle N_g \rangle$ vs R_2 dependence for pEm interactions

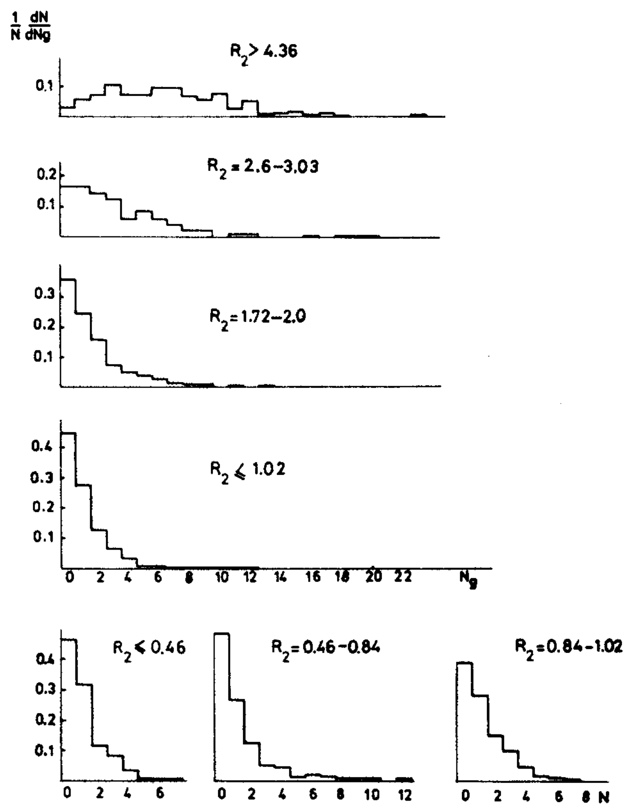

Fig. 7. The distributions of N_g at different values of R_2

For $R_2 \lesssim 1$ $\langle N_g \rangle$ depends weakly on R_2 and for $R_2 > 1$ the growth of $\langle N_g \rangle$ with growing R_2 is observed. Similar dependence of $\langle N_h \rangle$ on the normalized multiplicity for pEm interactions at 200 GeV was shown in the work of Andersson and Otterlund [12].

Fig. 7 shows that if one divides the region $R_2 \lesssim 1$ into three parts, one obtains similar N_g distributions in all parts. For $R_2 > 1$ the shape of N_g distributions changes with growing R_2. Of course this could already be expected on the basis of the dependence $\langle N_g \rangle$ vs R_2 (Fig. 6).

In our opinion the region of $R_2 \lesssim 1$ contains mostly jets produced in collisions of primary proton with single nucleons inside the nucleus.

For evaluating the admixture of jets with $R_2 \lesssim 1$ which are produced in two or three independent collisions we assumed that the multiplicity distributions in collisions with the nucleons inside the nucleus are the same as in elementary interactions at the appropriate

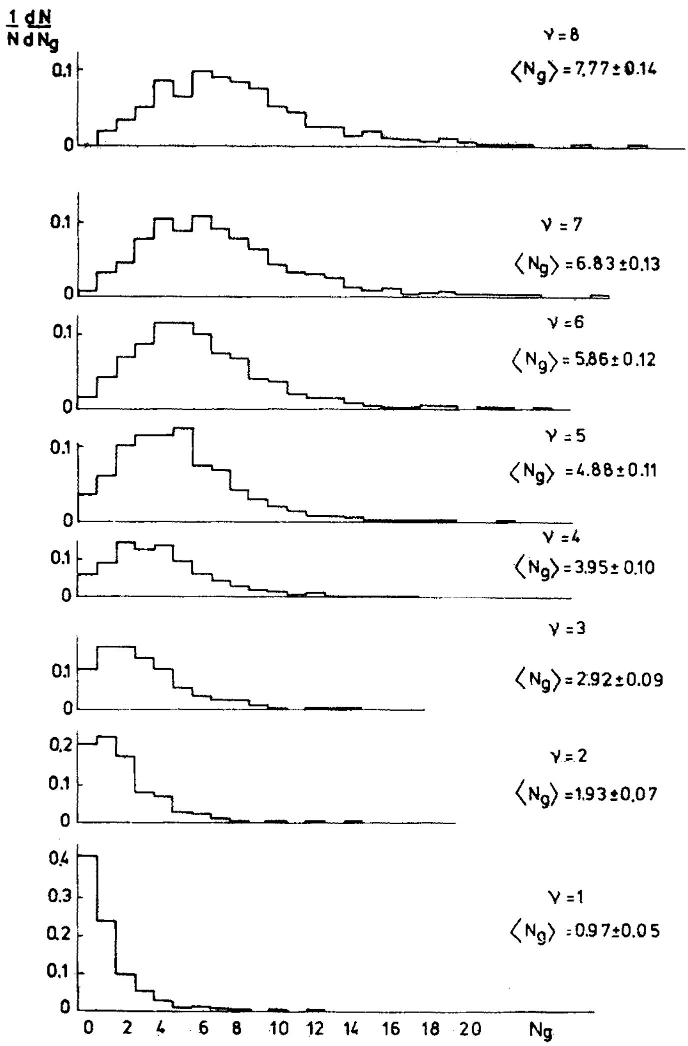

Fig. 8. The distributions of N_g at different values of ν

energies. Then knowing the multiplicity distributions in pp interactions we could evaluate that the correction for double collisions with $R_2 \lesssim 1$ is $\sim 10\%$ and the correction for triple collisions is negligible. Taking into account the correction for double collisions we obtained the N_g distribution for $\nu = 1$ which is presented in Fig. 8.

6. The distribution of N_g as a superposition of N_g distributions for single collisions. The ν vs N_g dependence

If grey tracks in p-nucleus interaction are produced in several independent collisions with the nucleons inside the nucleus, we can obtain N_g distributions for $\nu = 2, 3, 4...$ knowing the N_g distribution for a single collision (jets with $R_2 \lesssim 1$) and choosing at random

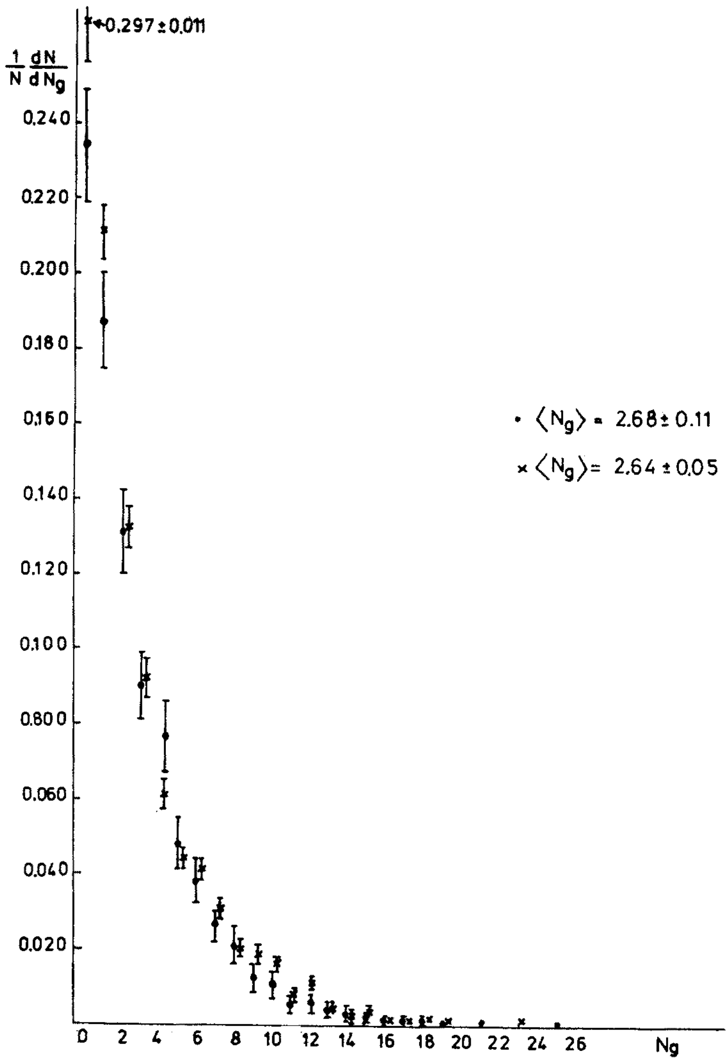

Fig. 9. The comparison of N_g distribution obtained from our analysis (points) with the experimental N_g distribution (crosses)

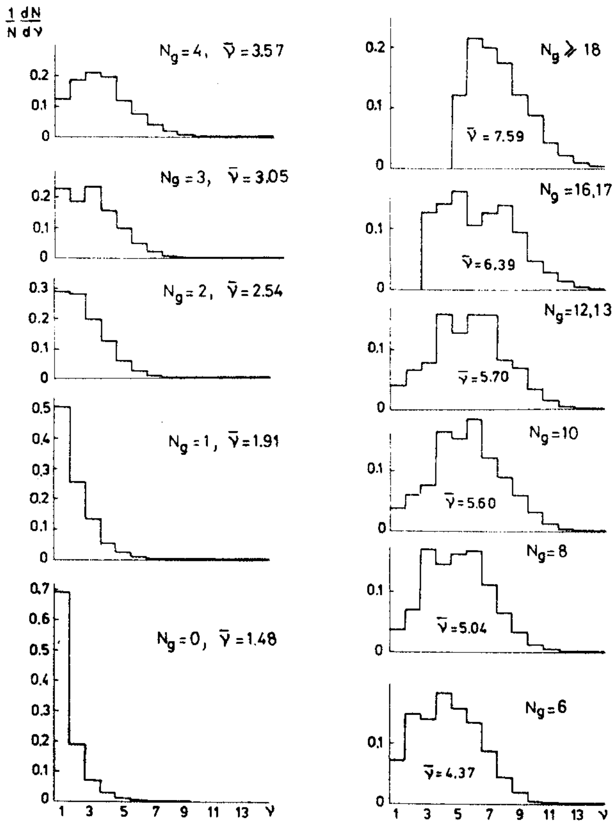

Fig. 10. The distributions of ν at different N_g

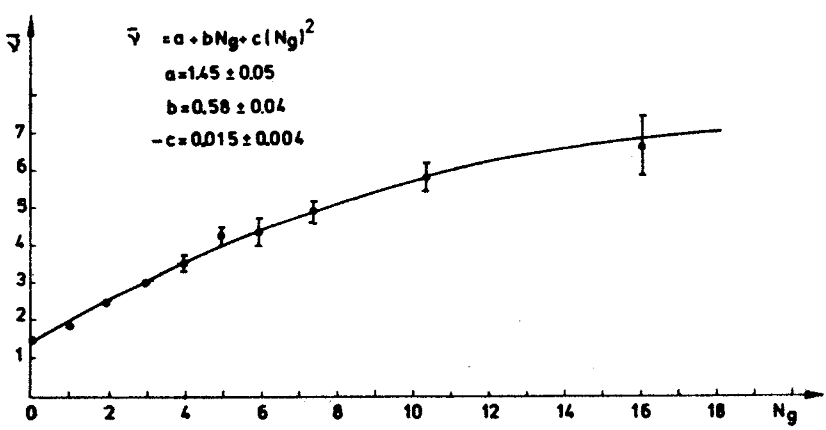

Fig. 11. The $\bar{\nu}$ vs N_g dependence for pEm interactions

the N_g distributions for other single collisions from the initial one. The distributions of N_g for $1 \leqslant \nu \leqslant 8$ are presented in Fig. 8. The fact that the N_g distribution for $\nu = 1$ is very narrow supports the hypothesis that the N_g is a good measure of the number of collisions. Next we multiplied N_g distributions for different ν by $P(\nu)$ for pEm interactions [5] and added them. Thus we obtained the N_g distribution for pEm interactions and compared it with the experimental one presented in Fig. 1. The χ^2-test showed the good agreement of both distributions presented in Fig. 9. This indicates the correctness of our procedure.

Knowing $P(\nu)$ and the N_g distributions for different ν we could calculate distributions of ν for different N_g presented in Fig. 10. In Fig. 11 the $\bar{\nu}$ vs N_g is shown.

7. The dependence R vs $\bar{\nu}$

Our further calculations deal only with pEm interactions at 200 GeV[2]. For these interactions we have a sample very large in comparison with other data available for us, namely 3065 jets. Several hundreds of our jets at 200 GeV pEm come from special scanning of jets with a large number of slow particles.

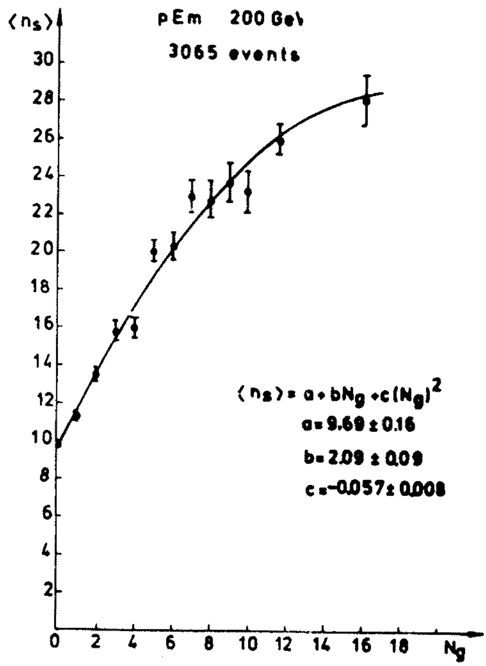

Fig. 12. The $\langle n_s \rangle$ vs N_g dependence for pEm interactions at 200 GeV

In Fig. 12 the experimental dependence of $\langle n_s \rangle$ i. e. average multiplicity of secondary relativistic ($\beta > 0.7$) particles on N_g for our sample of jets mentioned above is shown. The dependence $\langle n_s \rangle$ vs N_b for this sample is linear: $\langle n_s \rangle = (9.44 \pm 0.16) + (0.88 \pm 0.03)\, N_b$.

[2] All our considerations in this work deal with inelastic and incoherent interactions.

The dependences $\langle n_s \rangle$ vs N_g and $\langle n_s \rangle$ vs N_b for pEm interactions at 200 GeV were presented in the papers of Collaboration Alma-Ata and other Labs [13].

From experiment we know the mean multiplicity of relativistic particles $\langle n_s \rangle$ at different N_g in pEm interactions at 200 GeV and the mean number of all charged particles in pp interactions $\langle n \rangle_H = 7.68 \pm 0.07$ at the same energy [14]. If we want to calculate the

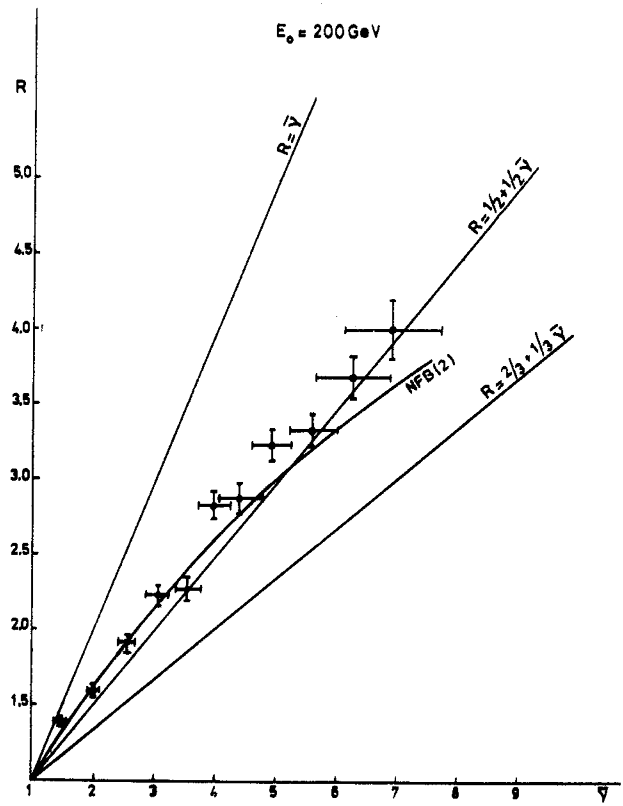

Fig. 13. The R vs $\bar{\nu}$ dependence (the change of $\bar{\nu}$ is realized by the change of N_g)

normalized multiplicity R i. e. the relation of the multiplicity in pEm interaction to the multiplicity in pp interaction, we must introduce the correction for slow particles. This can be done in two ways: we can calculate $R = \langle n_s \rangle / (\langle n \rangle_H - 0.62)$, where 0.62 means the average number of slow particles ($\beta < 0.7$) in pp interaction evaluated by Calucci et al. [7] (0.48 protons plus 0.14 pions) or we can calculate $R = (\langle n_s \rangle + \delta)/\langle n \rangle_H$, where δ is the average number of slow particles in pEm interaction (the correction δ depends on the mean number of collisions in the nucleus and was defined in work [4]). We stated that both methods of calculating R (the first of them was used in [15] and the second in [4]) give the same results in the limits of errors.

Thus we calculated R (by the first method) for different N_g and using the $\bar{\nu}$ vs N_g dependence (see Fig. 11) we were able to find the R vs $\bar{\nu}$ dependence up to $\bar{\nu} \approx 7$ (see Fig. 13).

In Fig. 13 some curves R vs $\bar{\nu}$ are shown which represent the predictions of three models of high-energy p-nucleus interactions. The line $R = 2/3 + 1/3\,\bar{\nu}$ resulting from the EFC model of Gottfried [16] distinctly disagrees with experimental data (it was shown previously e. g. in the works [2–4]). The line $R = 1/2 + 1/2\,\bar{\nu}$ results from the model of excited states of nucleons [2] and also from the modification of the EFC model (Calucci et al. [7], Friedländer [17]). The NFB curve was calculated using the model of noninteracting fireballs proposed many years ago for cosmic ray jets by Mięsowicz [18, 4]. In this model only primary particle interacts subsequently with some nucleons inside the nucleus and the products of these interactions (fireballs or other intermediate states with the baryonic number 0) do not interact inside the nucleus.

The calculations of the NFB model performed in this work are more accurate than those made in the work [4]. In this work we have taken into account the distributions of ν in the "mean" nucleus of emulsion at diffreent N_g and the distribution of inelasticity coefficient K. Namely we assumed that the distribution of K in the CM-system of colliding nucleons is rectangular (this seems to be reasonable although the experimental information about the distribution of K is spare [8]).

We have also taken into account the possibility of the interactions of recoil nucleons inside the nucleus which has only little influence on the results of calculations.

At the values of $\bar{\nu}$ not too large ($\bar{\nu} < 6$) the experimental points in Fig. 13 are in sufficient agreement with the curve NFB, whereas most of them lie above the line $R = 1/2 + 1/2\,\bar{\nu}$. For $\bar{\nu} > 5$ the agreement of this line with experimental points is good whereas the NFB curve lies slighty below them.

If one assumes the validity of the NFB model it may be supposed that the decay products of slow intermediate states (fireballs, clusters) which are decaying inside the nucleus can interact inside the nucleus. This effect has not been taken into account in our calculations and this might explain the disagreement of the NFB curve with experimental points for large $\bar{\nu}$. However, if it was desired to take into account this effect it would be necessary to make some assumptions concerning the physical properties of the intermediate states produced in elementary interactions.

8. *The dependence R vs $\bar{\nu}$ in various experiments*

The experimental data presented in Fig. 13 can be approximated by the linear dependence: $R = \alpha + \beta\bar{\nu}$ where $\alpha = 0.65 \pm 0.04$ and $\beta = 0.50 \pm 0.03$. In our previous works [19, 4] we also obtained $\alpha + \beta \neq 1$. From this fact one can conclude that the real dependence R vs $\bar{\nu}$ is non-linear. We think that there is no reason to assume a priori: $\alpha + \beta = 1$ as some authors do. Zalewski is of the same opinion [1].

If the dependence R vs $\bar{\nu}$ is non-linear, one can obtain the different R vs $\bar{\nu}$ dependences in various experiments in which the number of collisions is estimated by different methods. This may be so because in various experiments the same mean values $\bar{\nu}$ can be connected with different distributions of ν.

It is shown in Fig. 14 that the distributions of ν with almost the same values $\bar{\nu}$ are different in experiments in which the change of $\bar{\nu}$ is realized by means of the change of target (and thereby by the change of A) and in experiments in which the change of $\bar{\nu}$ is realized by the change of N_g (which has some connection with the change of impact parameter). The differences of the shapes of the distributions are more distinct with larger $\bar{\nu}$.

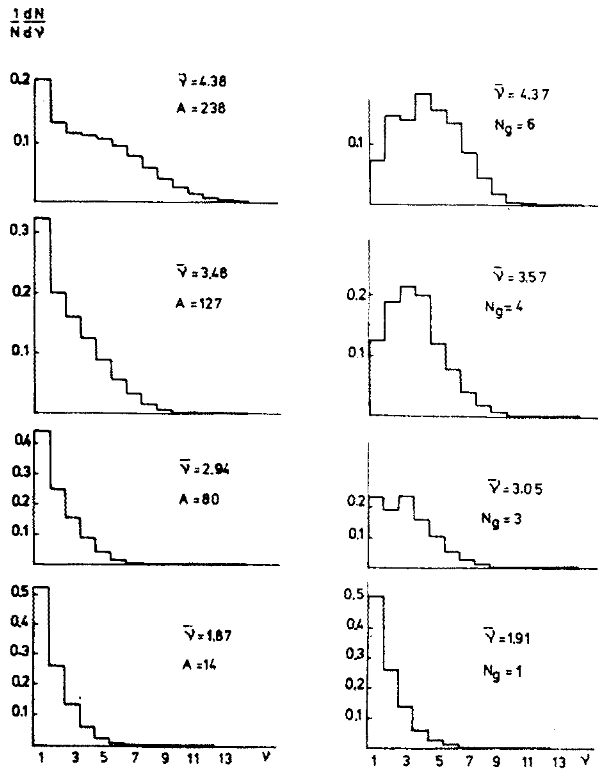

Fig. 14. The distributions of ν at different A and the distributions of ν at different N_g

We performed the same calculations based on the NFB model in three variants. (1) assuming the distributions of ν calculated theoretically [5] for the interactions of protons with the nuclei with different A; (2) assuming the distributions of ν calculated by us for pEm interactions at different N_g (Fig. 10); (3) assuming that the number of interactions of nucleon inside the nucleus is always equal to the mean value ($\nu = \bar{\nu}$) for a given target and taking $\nu = 1, 2, 3, 4$ ... Hence we obtained three curves presented in Fig. 15. These curves are different and although the difference between the curves (1) and (2) is small, it grows with the growth of $\bar{\nu}$.

Our experimental data were compared in Fig. 13 with the curve NFB (2), whereas the data of Busza et al. [3] ought to be compared with the curve NFB (1). It is seen in Fig. 16 that although data of Busza et al. are in very good agreement with the line $R = \frac{1}{2} + \frac{1}{2}\bar{\nu}$, they do not rule out the validity of the curve NFB (1). However, the emulsion data which also come from experiments with changing targets: CNO, Em, AgBr, W [15, 2, 20] are in somewhat better agreement with the curve NFB (1).

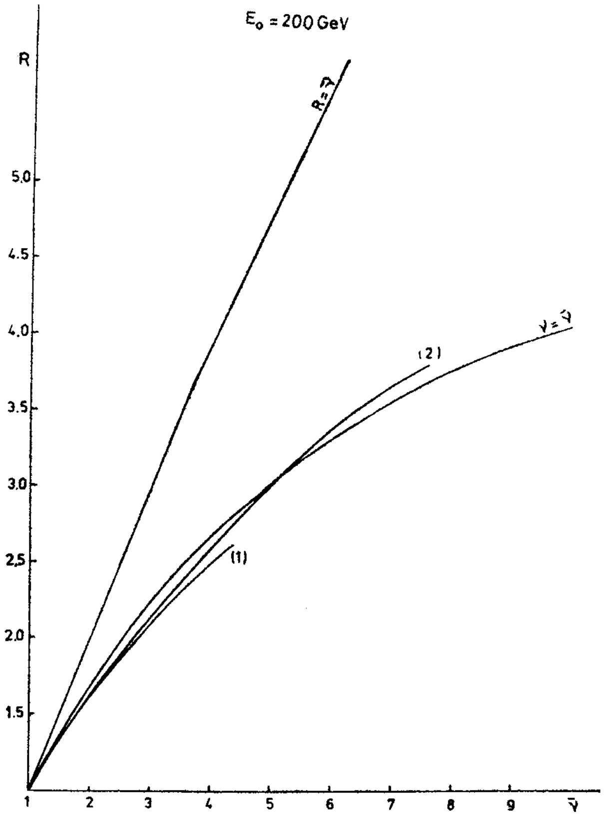

Fig. 15

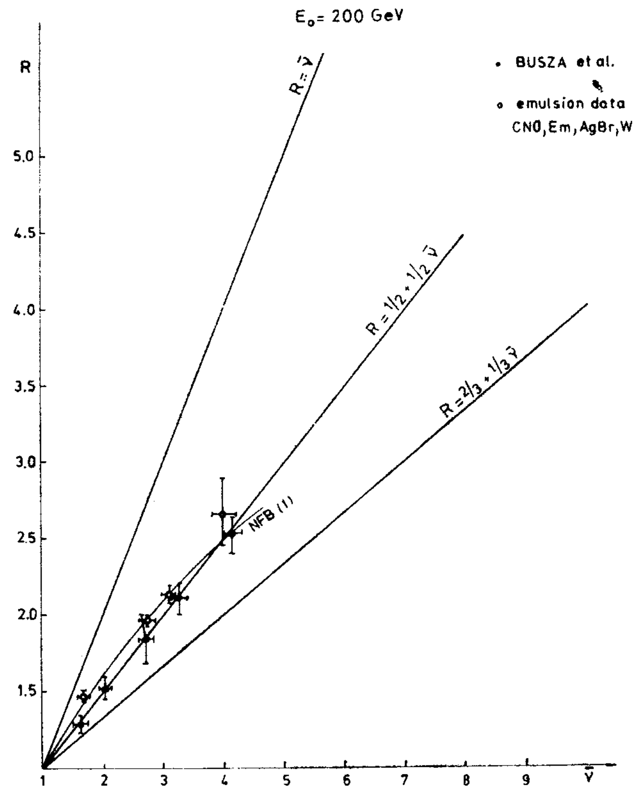

Fig. 16

Fig. 15. The NFB curves obtained by the same calculations performed in three variants (see Chap. 8)

Fig. 16. The R vs $\bar{\nu}$ dependence (the change of $\bar{\nu}$ is realized by the change of A)

It is worth emphasizing that the NFB calculations take into account the fact that the leading particle loses its energy in collisions with nucleons inside the nucleus. If the energy losses in collisions of the primary particle with nucleons were very small ($K \approx 0$) the NFB calculations at very large primary energies would give the dependence $R \approx \bar{\nu}$.

9. *Conclusions*

The analysis of slow particles produced in the interactions of hadrons with the nuclei of emulsion and divided traditionally into grey and black tracks shows the differences in some characteristics of these two groups of tracks and leads to the conclusions:

(a) The number of grey tracks N_g is a good measure of the number of collisions inside the nucleus.

(b) The analysis of grey tracks permits the finding of the dependence of the number of collisions $\bar{\nu}$ on N_g and thereby the dependence of the mean normalized multiplicity R on $\bar{\nu}$ up to relatively large values of $\bar{\nu}$ ($\bar{\nu} \approx 7$).

(c) The experimental dependence R vs $\bar{\nu}$ for pEm interactions at 200 GeV does not agree with the predictions of the EFC model ($R = 2/3+1/3\,\bar{\nu}$) but is close to the line $R = 1/2+1/2\,\bar{\nu}$.

(d) The experimental dependence R vs $\bar{\nu}$ is in sufficient agreement with predictions of the model of non-interacting fireballs (NFB) in which the primary particle interacts subsequently with nucleons inside the nucleus and the products of its interactions do not interact inside the nucleus.

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