COHERENT PROCESSES AT VERY HIGH ENERGIES

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The following processes were discussed:

The coherent bremsstrahlung emission of photons by electrons at ~ 1000 GeV.

The σ_{coh}-energy dependence for 3π- and 5π-production by pions in the energy interval 17 GeV — 200 GeV.

Interaction of pionic systems produced at very high energy with nucleons inside the nucleus.

The majority of investigations on coherent inelastic interactions performed recently in different laboratories, as well as the lectures given at the present school, concern coherent hadronic interactions limited to primary energies lower than 20 GeV.

Here I will speak about processes at very high energies, *i.e.* at Serpukhov and cosmic ray energies, and will not limit myself to hadronic interactions.

One of the most interesting and fundamental characteristics of coherent processes is, in consequence of a very small momentum transfer, a very large effective distance on which the process takes place.

For hadronic coherent interaction the effective distance of coherence limiting the momentum transfer equals the diameters of nuclei and corresponds to a momentum transfer to the nucleus of up to some scores of MeV/*c*, which is, of course small in comparison with the primary beam momentum, *e.g.* 20 GeV/*c*.

But I will recall here some coherent electromagnetic processes for which the effective distance of coherence contains, in dense material, thousands of nuclei. I mean here the emission of bremsstrahlung photons by electrons at very high energy, *e.g.* 1000 GeV. We shall see that this effective distance of coherence can be measured by an incoherent process, *i.e.* by multiple Coulomb scattering.

In my talk I will also deal with the studies of production of 3π and 5π systems by pions in a very large energy interval, namely between 17 GeV, Serpukhov energies

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(40 GeV and 70 GeV) and cosmic ray energies of some hundreds of GeV. Especially the problem of the energy dependence of the total cross-section σ_{coh} for production of 3π and 5π systems will be discussed.

The theoretical description of the coherent production follows the optical diffraction model including the absorption of the coherently produced pionic system in nuclear matter. We shall compare this picture with the absorption of the "pionic body" produced incoherently at ultra high energies in nuclear matter.

Here I will present mainly the result obtained by the Cracow Emulsion group. The Serpukhov results were obtained in a collaboration of many laboratories organized by the Dubna Emulsion Committee.

The idea of coherent phenomena in particle physics was proposed for the first time many years ago by Feinberg and his coworkers. I will refer here to the review article of Feinberg and Pomeranchuk [1].

1. The bremsstrahlung process in dense material

When a very high energy electron moves in a dense material and radiates bremsstrahlung photons, the momentum transfer to the nucleus is usually very small. Let us denote by E the primary energy of the electron and by k the energy of the emitted photon. The angle of emission of the photon referring to the primary electron is roughly $\theta_{\text{brems}} \simeq \frac{m}{E}$, where m is the electronic mass. Let us assume as an example $E \simeq 1000$ GeV, which will roughly correspond to our experiments. Int his case $\theta_{\text{brems}} \simeq 10^{-6}$. The longitudinal momentum transfer for so strong a collimation will be

$$q_{||} = \sqrt{E^2 - m^2} - \sqrt{(E-k)^2 - m^2} - k \simeq \frac{m^2 k}{2E(E-k)}.$$

For $E \simeq 1000$ GeV and *e.g.* $k = 0.5\,E$ we get for longitudinal momentum transfer $q_{||} \simeq 0.125$ eV/c. In consequence of this very low momentum transfer in these conditions, the bremsstrahlung process will take place on a very long distance and will be affected by a coherent action of many nuclei situated within the effective length

$$a_{\text{eff}} \simeq \frac{\hbar}{q_{||}} \simeq \frac{2E(E-k)\hbar}{m^2 k} \qquad \text{(see [2])}.$$

In the above-mentioned numerical example the effective length equals macroscopic values: $a_{\text{eff}} \simeq 1.6 \cdot 10^{-4}$ cm. A very important fact to be noted is that a_{eff} depends on the photon energy k. The effective length increases as k decreases.

Feinberg and Pomeranchuk noticed that if $\frac{k}{E}$ is sufficiently small for very high energies of electrons E, another important process must be taken into account, namely the Coulomb multiple scattering of electrons by the nuclei of the medium. This process may destroy the coherence between incoming and outgoing waves. If the scattering is sufficient to decline electrons through an angle larger than the angle in which bremsstrahlung is directed forward, *i.e.* θ_{brems}, then the coherence is destroyed.

Let us compare the mean angle of multiple scattering θ_{scatt} and θ_{brems}.

We have the known formula

$$\langle\theta^2_{\text{scatt}}\rangle = \left(\frac{E_s}{E}\right)^2 \frac{a_{\text{eff}}}{L} \qquad \text{(see \textit{e.g.} Rossi [2]).}$$

Here the "scattering constant" $E_s \simeq 21$ MeV, and L is the radiation unit. (We have, *e.g.*, for Pb $L \simeq 0.5$ cm and for emulsion $L \simeq 3$ cm). So the condition of "destroying" the coherence is $\left(\frac{E_s}{E}\right)^2 \frac{a_{\text{eff}}}{L} \gtrsim \left(\frac{m}{E}\right)^2$ and after introducing a_{eff} we have, according to Feinberg and Pomeranchuk,

$$\frac{E}{m} > \frac{1}{60}\sqrt{\frac{kL}{\hbar}}\,.$$

Thus we see that the "limits of coherence" depend on the energy of the radiated photons. This effect changes the usual spectrum of bremsstrahlung photons, the Bethe Heitler spectrum, giving a deficiency of low energy photons. This point of view had been worked out by Landau and Pomeranchuk (quoted in [1]) in a complete theory, many years before any experiments were started.

This change of the Bethe-Heitler-spectrum of bremsstrahlung photons was found experimentally by the Cracow group some years ago [3, 4].

Now I shall present some experimental details and results of this work. Four electromagnetic cascades of energies around 1000 GeV were selected in ultra high energy cosmic ray

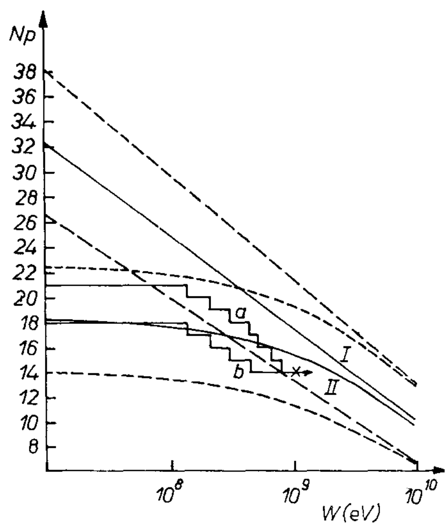

Fig. 1. Integral energy spectrum of electron pairs of the second generation. *Np*: number of pairs of energy greater than the given value *W*. *a*, *b*: experimental histograms (see text) *I*: Bethe-Heitler spectrum, *II*: Feinberg, Landau, and Pomeranchuk spectrum (primary electron energy 500 GeV). Curves *I* and *II* are given with their standard deviation. (From Ref. [4])

jets in emulsion. At the very beginning of a given cascade, which was well separated among the tracks of the jet we observed well-resolved electronic pairs of the second generation due to the conversion of bremsstrahlung photons. The origins of these pairs are very close to the electronic tracks and because of very high collimation the pairs show the so-called Chudakov effect [5, 6], *i.e.* the diminishing of ionization at the origin of the pair in consequence of partial cancellation of positon and negaton charges. This, combined with the opening angle, gives us the possibility of evaluating the energy of the pair. Fig. 1 shows the results of energy measurements of second generation pairs, performed by the Cracow group (from Ref. [4]). We see in the figure the integral energy spectrum of electron pairs and this spectrum is compared with the Bethe-Heitler spectrum (the straight line *I*). Histograms *a* and *b* represent the experimental spectra, taking into account the uncertainty of the order of generation of some electron pairs. Curve *II* presents the spectrum predicted by the theory of Landau *et al.* quoted in Feinberg's paper [1]. The deviation from the Bethe-Heitler spectrum observed here is quite significant.

Similar experiments with even better statistics were carried out by the Moscow group [7] and the Bristol group [8].

2. *Hadronic coherent interactions at very high energy with production of 3π- and 5π-bodies*

Here we will speak about the coherent production of particles in the reactions:

$$\pi^- + A \rightarrow \pi^-\pi^+\pi^- + A \tag{1}$$

$$\rightarrow \pi^-\pi^+\pi^-\pi^+\pi^- + A \tag{2}$$

$$\rightarrow \pi^-\pi^+\pi^-\pi^0\pi^0 + A. \tag{3}$$

Especially the reaction (1) has been extensively investigated in the 5–20 GeV energy interval, from the point of view of coherent production (or coherent dissociation). It has been found that the cross-section for coherent reaction (1) increases with increasing primary energy between 6 GeV and 16 GeV [9, 10].

A possibility of further increase in the cross-section for this reaction was suggested by the Cracow group on the basis of several coherent 3π events found at an average energy about 200 GeV in cosmic ray jets [11].

3. *Serpukhov energies*

I shall now report the investigations carried out by the Dubna collaboration. They were performed using 45 GeV/c and 60 GeV/c π^- beams of the Serpukhov accelerator [12, 13, 14]. Blocks of emulsion of typical size 20 cm × 10 cm × 0.06 cm × 100 pellicles were irradiated in the beam. A very extensive scanning along the tracks was performed. As an example, I may mention that for 60 GeV/c — 3147 m of tracks have been scanned and 7012 inelastic interactions found. This corresponds to the mean free path of pions in nuclear emulsion $\lambda_{\text{int}} = 43.7 \pm 0.6$ cm. Out of all these interactions we have selected those with at most one non-relativistic particle emitted into the forward laboratory hemisphere. For 60 GeV/c we selected in this way 1334 interactions. Usually in emulsion work we consider this type of event as an elementary collision, *i.e.* either with free protons or with one single nucleon of the target nucleus. It was shown and published in papers of our collaboration [12, 13] that the prong-number distribution of shower particles in these events shows an overabundance of three prong events. But this overabundance appears only in the prong-number distribution of the "clean" events, *i.e.* of those interactions in which there is neither a visible recoil proton nor accompanying electrons, as should be expected for coherent events. It should be mentioned that the resolution of nuclear emulsion allows us to observe fairly slow recoils (0.2 MeV for protons and $\sim$ 1 MeV for a carbon nucleus). The prong-number distribution becomes a smooth one after removing 197 ± 16 events as belonging to a process other than the usual particle production, *i.e.* to the coherent production.

Another estimation of the number of coherent events can be made by comparing the collimation of secondaries in "clean" and "dirty" events, among three prong stars. As a measure of this collimation a parameter $\Sigma \sin \theta_i$ has been adopted. This parameter was frequently used in previous works of coherent interaction in emulsion and is roughly proportional to the longitudinal momentum transfer $q_{\parallel}$ to the target nucleus. We have, namely, as a necessary condition of coherent production of particles m_i, occurring in collision with a nucleus: $\Sigma m_i \sin \theta_i \leqslant m_\pi A^{-1/3}$ and when only pions are produced: $\Sigma \sin \theta_i \leqslant A^{-1/3}$. For emulsion, after subtracting the hydrogen nuclei, we have $\langle A_{\text{eff}} \rangle \simeq 40$ and the necessary condition of coherence: $\Sigma \sin \theta_i \lesssim 0.3$.

It was shown [12, 13, 14] that the frequency distribution of this parameter $\Sigma \sin \theta_i$ may help us in the identification of coherent events. The distributions for "clean" and "dirty" events differ distinctly. For "clean" 3-prong events, the distribution shows a distinct peak for small values of $\Sigma \sin \theta_i$. The number of coherent events evaluated by subtracting an extrapolated background in $\Sigma \sin \theta_i$ distribution agrees very well with the number determined from the prong number distribution.

The analysis of 3π-systems at 45 GeV has been performed in a similar way. However, in older papers of our collaboration [12, 13] the statistics at 45 GeV was rather poor. Recently the Tashkent group performed extensive investigations at 45 GeV [15] as well as at 17 GeV [16] by scanning about 2.6 km and 7 km track lengths for those energies respectively[1].

For a given number of coherent interactions and track length, the mean free path λ_3 for 3π coherent production has been calculated. In Table I all the data are summarized. It should be stressed that the experimental procedure for evaluating λ_3 for 17 GeV, 45 GeV, and 60 GeV was identical, so the decrease in λ_3 observed in Table I. *i.e.* the increase in σ_3, the cross-section for coherent 3π production, with increasing primary energy is therefore very significant.

The reaction $\pi^- \rightarrow \pi^-\pi^+\pi^-\pi^+\pi^-$ was observed at 15–17 GeV [17, 18]. Unfortunately, the prong-number distribution for 60 GeV has its maximum near the value $n \simeq 5$. Consequently the observation of any overabundance of five-prong coherent events is very difficult. But we can recall the distribution of the collimation parameter $\Sigma \sin \theta_i$, which

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[1] We are very much indebted to the Tashkent group for informing us about the new results.

gives us 23.7 ± 8 five-prong coherent events. The corresponding mean free path λ_5 and cross-section σ_5 are summarized in Table I. The values for 45 GeV are again taken from the data of the Tashkent group [15].

TABLE I

Summary of the coherent production in emulsion

	7.5 GeV/c	17 GeV/c	45 GeV/c	60 GeV/c	$\langle p \rangle \simeq$ 200GeV/c
Traced length (m)		7656	2630	3062	60.3
N_3 from n_{ch} — distr			117 ± 5	197 ± 16	7.0 ± 3
N_3 from $\Sigma \sin\theta$ — distr			110 ± 13	197 ± 12	
λ_3 (m)	178^{+153}_{-56}	53^{+7}_{-5}	23.2 ± 3	15.6 ± 2	10.3 ± 4
σ_3 (mb)	1.16 ± 0.5	4.11 ± 0.45	8.95 ± 0.9	13.2 ± 0.8	20.7 ± 8
$\sigma_3/A^{2/3}$ (mb)	0.10 ± 0.04	0.31 ± 0.03	0.74 ± 0.08	1.10 ± 0.07	1.69 ± 0.66
N_5 from $\Sigma \sin\theta$ — distr		2	11.4 ± 4.6	23.7 ± 8	2
λ_5 (m)			231 ± 115	129^{+68}_{-34}	
σ_5 (mb)		0.06 ± 0.04	0.90 ± 0.4	1.60 ± 0.57	
$\sigma_5/A^{2/3}$ (mb)		0.005 ± 0.003	0.074 ± 0.03	0.133 ± 0.05	

Knowing the number of $\pi^-\pi^+\pi^-\pi^+\pi^-$-events we can evaluate the number of $\pi^-\pi^+\pi^-\pi^0\pi^0$ events from isospin considerations and in this way introduce a correction to the observed number of $\pi^-\pi^+\pi^-$ events. But it appeared that this correction does not give a significant difference in comparison with the previously given values of λ_3 in the

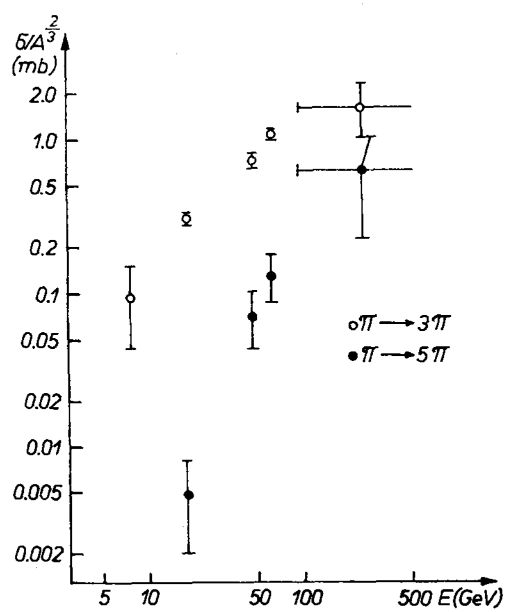

Fig. 2. "Normalized" cross-section $\sigma_{coh}/A^{2/3}$ for the coherent reactions $\pi^- \to 3\pi^\pm$ and $\pi^- \to 5\pi^\pm$ as a function of the primary energy

limits of error of this experiment. The correction was therefore not introduced in Table I and Fig. 2.

Although the σ_{coh}-dependence on atomic number A of the nucleus is rather complicated, the data of σ_3 and σ_5 in Table I are "normalized" by division by a constant factor $A^{2/3}$ so that they may be compared with elementary cross-sections.

4. Cosmic ray energies

As everybody knows, there are many difficulties in quantitative investigations of interactions with cosmic rays as the source of particles. However, we believe that the main disadvantage of earlier emulsion work was the method of scanning in order to collect a proper sample of events. Not only "area scanning", but also scanning for high energy interactions by means of electromagnetic cascades, used very often in jet work, give considerable preference to interactions with a high multiplicity. Until quite recently the low multiplicity events had not been investigated in cosmic ray jet work. But using very large emulsion stacks in nucleonic jet investigations we can follow nucleons which are the products of fragmentation of heavy primaries of cosmic rays. In investigation of pionic jets we can follow the secondaries (mainly pions) of very high energy nucleonic jets. In this way a systematic scanning along the tracks is possible which yields an unbiased sample of jets. Here the very low multiplicity events could be included in the analysis.

Our experiment was carried out in two very large emulsion stacks of the Chicago collaboration, each of the size $60 \times 45 \times 30$ cm^3 (~ 80 l) irradiated by cosmic rays at high altitude [11]. Of these about 75 litres were used in this work. We scanned along the tracks of secondary particles of 36 jets initiated by primary nucleons of energy higher than 1000 GeV. Over the total length $\sim$ 58 m — 144 secondary interactions were found. The energies of these secondaries were very roughly estimated from their emission angle, assuming a constant transverse momentum of 0.4 GeV/c. The resulting mean energy is $\sim$ 200 GeV with a considerable spread. It was shown by the Cracow group [11] that the distribution of multiplicity of shower particles n_s and of the number of evaporation tracks N_h, shows a striking peak at multiplicity $n_s = 3$ and $N_h = 0$. For events with $N_h > 0$ we observe a fairly smooth distribution with the most probable value $n_s \simeq 8$, and the mean value $\langle n_s \rangle \simeq 12$. The difference between these two distributions, *i.e.* for $N_h = 0$ and $N_h > 0$, suggest that they correspond to different processes. We have an additional argument for interpreting these events in terms of coherent production in collisions of pions with emulsion nuclei. I mean here strong collimation of produced particles measured by the small value of the $\Sigma \sin \theta_i$ parameter. Both arguments have been used for the selection of coherent events. The figures given in Table I for cosmic ray pions are based on the full material of the Cracow laboratory [11], [19].

5. Energy dependence of the cross-section for coherent production

The results collected in Table I concerning the cross-section for coherent production of 3π- and 5π-systems are shown in the diagram presented in Fig. 2. All the data concern emulsions and were obtained by the same type of scanning and selection of events. We see from the figure, which is the main result of this investigation, a very significant increase in the cross-section σ_{coh} for the process $\pi \rightarrow 3\pi$, when the energy increases from 16 GeV up to 60 GeV. A further increase in this cross-section, *i.e.* between 60 and 200 GeV, is also possible but the statistics for cosmic ray energies is so poor that this cannot be considered as significant.

It seems that for the cross-section σ_{coh} for the process $\pi \rightarrow 5\pi$ we have a similar situation.

It is beyond the scope of this paper to discuss in detail the theoretical interpretation of the energy dependence of the coherent production, so I am limiting myself to some remarks only.

One of the main properties of two-body processes is the decrease in the total cross-section for a given reaction with increase in the primary energy. It is in these cases $\sigma \sim p^{-n}$, with the exception of diffraction reactions for which cross-sections are energy independent. This constancy of the cross-section for diffraction processes is nicely described by Pomeron exchange in the Regge picture. We are speaking here, of course, about elementary hadron interactions. But, as we see, for coherent diffraction processes on nuclei, the cross-section increases with increase in the primary energy. One can try to explain this effect, for a given mass M of a coherently produced system, by the energy dependence of the minimum four-momentum-transfer t_{min}. We have namely: $t_{min} \simeq \left(\frac{M^2 - m^2}{2p}\right)^2$, where m is the mass of the beam particle and p is its primary momentum. The cross-section increase follows from the change of integration in integrating $\frac{d\sigma}{dt}$ [20]. But this explanation is valid only at low primary energies for which $t_{min} \simeq 1/B$ (B is the exponent in the cross-section: $\frac{d\sigma}{dt} \sim e^{Bt}$). It is however easily seen that this effect reaches saturation for fairly low primary energies (*e.g.* 20 GeV).

At higher energies larger masses of the produced system are allowed. The maximum mass which can be produced coherently is $M_{max} = \sqrt{m_\pi^2 + \frac{2p}{R}} \sim \sqrt{p}$ (R is here the radius of the nucleus) so the number of possible pion states increases. For a given number of pions in the final state we can have, for instance, for the 3π system, new higher masses (see *e.g.* Bingham [21]). We can say that the distribution of the 3π-mass is wider for higher primary momenta.

On the other hand, we must bear in mind that the summarized cross-section for coherent production of all pionic systems increases because for higher primary momenta new pionic systems can be produced with a higher number of pions in the final state. It was suggested [22] that the dissociation process $\pi \rightarrow 3\pi$, 5π, 7π, *etc.* has a "ϱ-structure". Up to now only 3π and 5π systems have been observed with maxima of the mass distribution at 1.1 GeV and 1.9 GeV for 3π and 5π respectively. Assuming this ϱ-structure in the dissociation process for heavier pionic systems, we can expect the following masses M of the pionic systems and minimum necessary primary beam momenta:

	3π	5π	7π	9π	
M	1.1	1.9	2.6	3.4	GeV/c^2
p	12	36	66	110	GeV/c

The problem of the production of multipion systems and their interaction inside the nuclei is very interesting and therefore the proposal for experiments at Serpukhov and Batavia are very promising [22, 23].

6. *Interactions of multipion systems inside the nucleus*

A rather general theoretical description of coherent multipion production used by many authors (see *e.g.* [24]) is the optical diffraction model with absorption of the multipion system inside the nucleus. It turned out that in order to obtain a good fit with experiment, *e.g.* for the dependence of σ_{coh} on the atomic number A of the target nucleus or on the mass M ot the produced pion system, it is necessary to assume that the attenuation of the produced multipion system inside the nucleus is small. The cross-section of the produced system for interaction with nucleons, *e.g.* $\sigma(3\pi, n)$, is equal to or even smaller than the cross-section of the beam pions $\sigma(\pi, n)$.

The very interesting problem of the σ_{coh}-energy dependence shown in Fig. 2 has been investigated by Leśniak and Leśniak [25]. They explain the increase of σ_{coh} for producing 3π and 5π by pions on Ag nuclei with increasing primary energy from 16 GeV to 200 GeV by the decrease of the longitudinal momentum transfer with increasing energy. This is connected with the increase in the width of the 3π-mass distribution with increasing energy. Also in this work the interaction cross-section of the 3π system, $\sigma(3\pi, n)$ must be taken quite small, roughly equal to $\sigma(\pi, n)$.

It has been proposed [24] that the evaluation of $\sigma(3\pi, n)$ cross-section can give the possibility of deciding whether the A_1-enhancement in the 3π-mass distribution may be considered as a resonance, or only a kinematical effect in the production of ϱ and π not dynamically bound. The low value of $\sigma(3\pi, n)$ cross-section observed on the basis of fitting this parameter in the diffraction model seems to support the hypothesis that A_1 is in fact a resonance. But recent investigations show that the distinction between the two hypotheses on the basis of experiments of this type is doubtful [26].

Recent measurements of Bemporad *et al.* [18] performed on many nuclei from Be to Pb give the cross-section for interaction of the multipion system with nucleons. These measurements, performed with very good statistics, show again that the $\sigma(3\pi, n)$ cross--section is roughly equal to $\sigma(\pi, n)$ and $\sigma(5\pi, n)$ is even smaller. However according to the authors, the 3π-mass distribution does not show the A_1 as a relatively narrow peak, but as rather structureless wide enhancement. So one cannot consider the low value of $\sigma(3\pi, n)$ cross-section as a property of the A_1-resonance.

I think that there is some evidence that the attenuation of groups of pions produced in incoherent interactions at ultra-high energy in nuclear matter is also small.

As we known frcm many cosmic ray investigation at an energy, *e.g.*, 1000 GeV, the mesons produced in nucleon-nucleon interactions in the pionization process are in most events divided into two groups flying in the CM system in opposite directions, following the colliding nucleons (two fireballs [27], [28]).

Hołyński *et al.* [29] studied interactions of primary nucleons with energies $\sim$ 1000 GeV with heavy nuclei in emulsion. To fit the experimental results, the authors proposed the following model for head-on nucleon-heavy nucleus collisions at ultra-high energies. They considered subsequent elementary collisions of the primary nucleon with several nucleons of the target nucleus, and their assumptions are: (*1*) Fireball production in elementary collisions. (*2*) Small inelasticity in elementary collisions ($K \simeq 0.3$), and (*3*) No interaction of fireballs inside the nucleus.

This model was supported recently by the studies by the Cracow group of interactions produced by nucleonic fragments with the nuclei in photographic emulsion. The primaries of these interactions are nucleons of known energies, so in these experiments the study of the symmetry of particles emission in the CM system of the primary nucleon and the nucleon of the target nucleus was possible. The authors have shown (Wolter [30], Rybicki and Wolter [31]) that in more than 80% of interactions of nucleons with nuclei of emulsion, the emission of particles is symmetric in the nucleon-nucleon CM system. In other words, in 80% of events we do not observe the development of an intranuclear cascade. This means that at ultra high energies the groups of produced mesons (fireballs) traversing the nucleus do not interact with the nucleons inside the nucleus very often.

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