ANALYSIS OF INELASTIC COLLISIONS OF PARTICLES WITH NUCLEI AT VERY HIGH ENERGIES

By V. S. Barashenkov and S. M. Eliseev

Joint Institute for Nuclear Research, Dubna*

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The experimental data on pion- and nucleon-nucleus interaction at energies considerably higher than 10 GeV are analysed on the basis of the intra-nuclear cascade model including a decrease in the number of intra-nuclear nucleons during the cascade development. Experiment and theory can be fitted at energies up to $T \approx 100$ GeV within experimental accuracy. At higher energies the calculated multiplicity of shower particles noticeably exceeds the experimental values. The effects of many-particle interactions are discussed from this point of view.

In Refs [1]-[4] it has been shown that at energies $T > 10$ GeV a strong discrepancy exists between the conventional intra-nuclear cascade model and experiment[1]. This discrepancy can be eliminated if one takes into account many-particle interactions inside the nucleus. The relative contribution of these interactions, determined from comparing the results of intra-nuclear cascade calculations with experimental data appears to be rather significant even at energies of about several tens of GeV [2]. However, the latest experimental information based on cosmic ray studies and on experiments at the 70 GeV accelerator at Serpukhov provides us with a deeper understanding of both the interactions of particles and the collisions of particles with nuclei at very high energies. During the recent years considerable progress has also been achieved in the cascade-evaporation model owing to the inclusion of the changes in the target nucleus properties in the course of intra-nuclear cascade [5]-[7]. Therefore the conclusions drawn in Refs [1]-[4] can be regarded as only tentative. All this has inspired us to revert to the problem of the applicability of the cascade-evaporation model and of the contribution of many-particle interactions at energies $T > 10$ GeV. These problems are the main subject of the present paper.

In order to find, with the highest possible accuracy, the points of discrepancies between the results of the experiment and intranuclear cascade evaporation model without the

* Address: Joint Institute for Nuclear Research, Head Post Office, P. O. Box 79, Moscow, USSR.

[1] In this paper T denotes the lab. system kinetic energy of the initial particle.

inclusion of many-particle interactions, calculations were performed using the same codes as those employed for the region of accelerator energies $T < 30$ GeV, where the results agree well with experiment [7]. In particular, the decrease in the density of the nucleon number in the target nucleus was taken into account [6]. The methods of calculating high-energy π–N and N–N collisions inside the nucleus were essentially different.

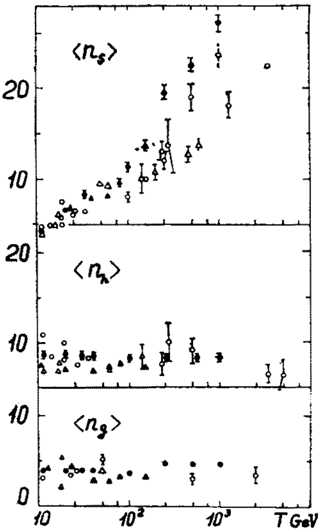

Fig. 1

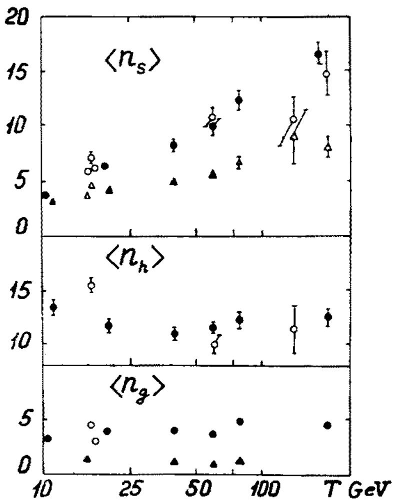

Fig. 2

Fig. 1. Energy dependence of the average multiplicity of particles produced in inelastic interactions of protons and pions with photoemulsion nuclei. n_s and n_g are numbers of particles leaving thin and grey tracks, and n_h is the average number of particles leaving grey or black tracks. Circles and triangles correspond to interactions $p+E$ and $\pi+E$, respectively. Shaded circles and triangles represent results of calculations, open ones are experimental data [10], [11]

Fig. 2. Energy dependence of the average multiplicity of particles produced in inelastic interactions of pions with light and heavy nuclei of photoemulsion. n_s, n_g and n_h have the same meaning as in Fig. 1. Circles and triangles correspond to the interactions $p+HEm$ and $p+LEm$, respectively. Shaded and open marks represent theory and experiment, respectively [10, 12]

In the region of $T > 30$ GeV one took account of the leading particle the energy of which was sampled by the experimental distribution of the inelasticity coefficient K. For the determination of the energies of other secondary particles from inelastic π–N and N–N collisions, polynomial approximations of the known experimental distributions were used; the dependence of these distributions on the particle emission angle was taken into account, and in every case of π–N and N–N interactions the law of energy-momentum conservation was accurately satisfied [8]. The calculated characteristics of the inelastic π–N and N–N collisions agree well with experiment over the entire energy range up to and including several thousands of GeV.

In view of the poor knowledge of the antibaryon multiplicity in high-energy π–N and N–N collisions (it is equal to $\approx 5\%$ and 10% of the total number of secondary part-

TABLE I

Average multiplicities of charged shower and slow particles in photoemulsions stars produced by 60-GeV pions

	Shower particles		Slow particles	
n_h	Theory	Experiment [11]	Theory	Experiment [11]
$0\div1$	3.9 ± 0.3	6.18 ± 0.11	0.35 ± 0.03	0.42 ± 0.03
$2\div7$	6.3 ± 0.3	7.61 ± 0.11	$4.4\ \pm0.2$	4.03 ± 0.03
$\geqslant 8$	$11\ \ \pm0.6$	11.77 ± 0.13	$13.3\ \pm0.9$	15.22 ± 0.15
$\geqslant 0$	8.1 ± 0.4	9.23 ± 0.07	$7.2\ \pm0.3$	7.02 ± 0.05

icles for π–N and N–N collisions, respectively), we do not consider any annihilation processes here.

The calculation of elastic interactions of particles inside the nucleus at $T > 30$ GeV has been performed using the polynomial approximations from Ref. [8]. At high energies

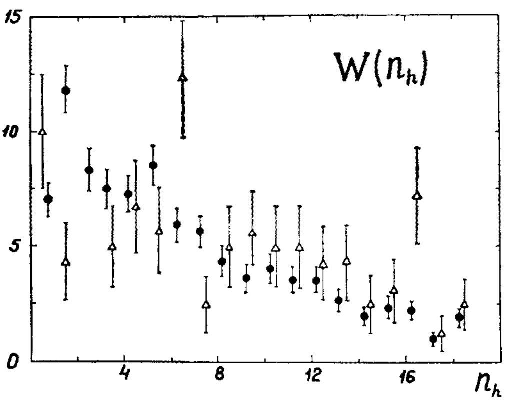

Fig. 3

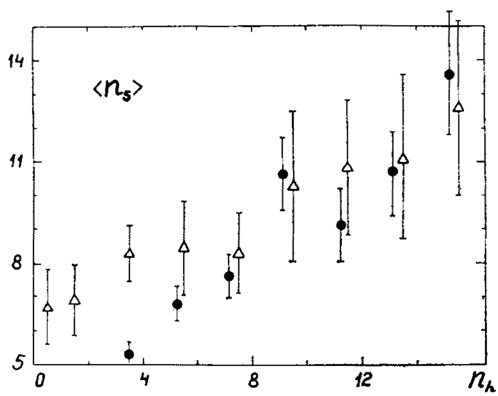

Fig. 4

Fig. 3. Distribution of grey and black tracks in stars produced in interactions of 60-GeV pions with photoemulsion heavy nuclei. Shaded and open triangles correspond to calculation and experiment, respectively [12]

Fig. 4. Average multiplicity of thin tracks in stars with different numbers of grey and black tracks produced in inelastic collisions of 60-GeV pions with photoemulsion heavy nuclei. Shaded and open triangles correspond to calculation and experiment, respectively [12]

the angle of scattering was sampled by the differential cross-section $d\sigma/dt = Ae^{-\beta(T)t}$ with coefficients A and β taken from Ref. [9]. Since scattering occurs at very small angles, a further detailing of the angular distributions does not practically enhance the accuracy of calculations.

As may be seen from Figs 1 and 2, where comparisons between the calculated and experimental values of the average multiplicity of particles from photoemulsion stars are

TABLE II

Average excitation energies of residual nuclei and the average number of nucleons lost by the target nucleus during the cascade

Interaction	T (GeV)	E^* (MeV)	A
$p+LEm$	60	30	2.0
$p+Em$	60	110	12.9
$p+HEm$	60	150	19.3
$p+Em$	250	154	17.4
$p+Em$	500	160	18.2
$p+Em$	10^3	163	18.6

shown[2], a more precise simulation of inelastic π–N and N–N interactions and the inclusion of a decrease in intra-nuclear density resulting from the effects of the avalanche of cascade particles allow us to obtain agreement with experiment in the energy region up to $T \approx 100$ GeV[3]. This is also related to the distribution of the multiplicities of the particles produced and their correlations (see Table I and Figs 3 and 4). A substantial discrepancy exists only in the case of shower particles in stars with $n_h = 0,1$. The reason for this discrepancy is that, in addition to pion-nuclear interactions, the observed events contain also a considerable contribution from π–N-collisions in which the multiplicity of shower particles is $n \approx 10$ [8]. If these collisions are taken into account, the calculated value of W for $n = 0,1$ is the same as the experimental one. Noticeable discrepancies which cannot be easily eliminated by varying the parameters which describe inelastic π–N and N–N collisions (without reaching beyond the limits permitted by modern experimental data) take place only at energies $T \approx 150$–200 GeV.

Table II shows that the excitation energy of the nucleus after the cascade phase and the number of nucleons lost by the target nucleus are on the average the same as those at $T \approx 10$ GeV. This provides an explanation of the reason why the number of grey and black tracks in Figs 1 and 2 is almost independent of the energy of the initial particle[4].

As regards the angular characteristics of secondary particles, theory and experiment are in rather good agreement (see Figs 5 and 6). There is also fairly good agreement in the region of high energies. However, one should not attach too much significance to this agreement since discrepancies between theory and experimental data for shower particles may be to a considerable extent masked by the relativistic transformation of angles as one passes to the laboratory coordinate system. A comparison of experimental and theoretical angular distributions in the system of the centre of mass of the projectile and the target

[2] The following notation is used here: Em is an interaction with a photoemulsion average nucleus; LEm and HEm are interactions with the groups of photoemulsion nuclei, light and heavy, respectively.

[3] The errors in the calculated values of Fig. 1 and further are purely statistical.

[4] If the calculations do not take into account the effect of decrease in intra-nuclear density, anomalously large values of A and E are obtained already at $T \approx 1$ GeV [13]; this results in very large values of n_g and n_h.

nucleus would be more illustrative. Unfortunately there are no relevant experimental data yet.

Fig. 7 presents a comparison of the calculated and experimental average transverse momenta of the particles produced. In the region of $T > 100$ GeV, the values of $\langle P_{\perp s} \rangle$ remain practically constant, at high energies the transverse momentum of π-mesons remains

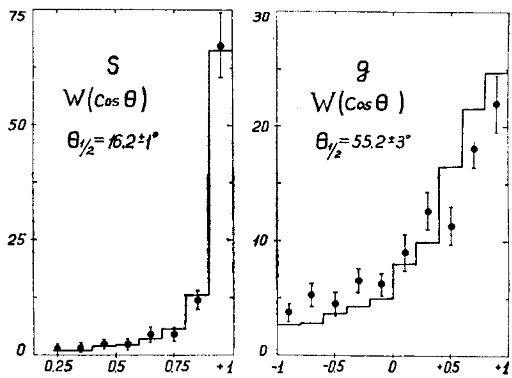

Fig. 5. Angular distributions of particles with thin and grey tracks in stars produced in inelastic collisions of 60-GeV pions with photoemulsion heavy nuclei. Histograms represent calculation, experimental points are from Ref. [14]. Calculated emission angles for a half of secondary particles are indicated

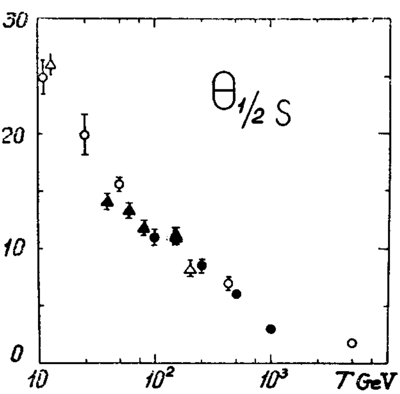

Fig. 6

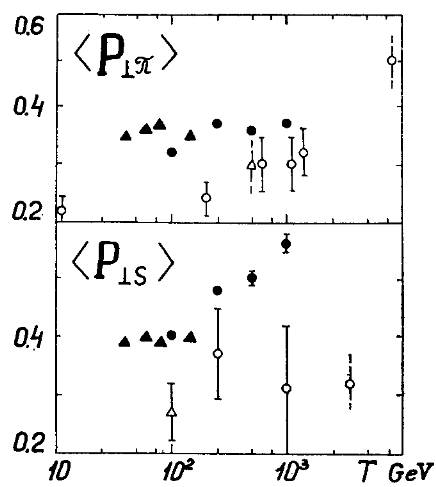

Fig. 7

Fig. 6. Variation of the emission angle of a half of the charged shower particles produced in inelastic collisions of protons and pions with photoemulsion nuclei with increasing energy ($\theta_{1/2}$ in degrees). Designation the same as in Fig. 1

Fig. 7. Energy dependence of average transverse momenta of pions and all charged shower particles produced in inelastic collisions $p+Em$ and $\pi+Em$ ($P_\perp$ is in GeV/c). Designation the same as in Fig. 1

unchanged (for the interactions $p+Em$), and the quantity $\langle P_{\perp s}\rangle$ increases slowly due both to the large contribution from the leading particle and to the increase in transverse momenta of the remaining nucleons.

The average transverse momenta of particles with grey tracks are independent of the primary energy within the limits of statistical errors. For instance, for collisions $p+Em$ at $T=250$ and 10^3 GeV $P_{\perp}=320$ and 360 MeV/c.

Thus a more precise re-establishment of the characteristics of the inelastic π–N and N–N interactions and mainly the inclusion of a decrease in intra-nuclear density during the cascade development permit agreement to be reached between the cascade-evaporation model and the known experimental data for energies $T<100$ GeV. To reach agreement with experiment at high energies, it is necessary to introduce into the theory a mechanism diminishing the number of the shower particles produced. Many-body interactions may serve as such a mechanism [2].

It should be emphasized that on the basis of the agreement between calculation and experiment in the region of $T=10\div100$ GeV one cannot conclude with certainty that the portion of many-particle interactions is negligibly small here since in this region only a small number of average quantities rather roughly characterizing the interaction have been studied experimentally. Some estimates indicate that taking into account many-particle interactions affects comparatively weakly these characteristics at $T\approx10\div100$ GeV.

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