объединенный
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дубна

E1-81-436

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INELASTIC INTERACTIONS OF 4.5 GEV/C PROTONS WITH EMULSION NUCLEI NOT ACCOMPANIED BY RELATIVISTIC CHARGED PARTICLES

Submitted to "Physica Scripta"

1981

1. INTRODUCTION

At present it is widely recognized that the study of multiple production on nuclear targets, which is a dominating process starting from energies of several GeV per incident particle up to the highest cosmic ray energies, is also of great interest for particle physics, mainly, because it offers important and unique information on the structure of hadrons or the space-time structure of particle production. Here we examine a different type of process which is in a sense complementary to the first one, and, thought it is of low energy character, as we will show later on in more detail, it can compete with the process of multiple production at not very high energies as well.

In this paper we have tried to understand inelastic interactions of 4.5 GeV/c protons with emulsion nuclei which are not accompanied by the production of relativistic ($\beta > 0.7$) charged particles. The importance of this type of process was first fully recognized in a series of papers full list of which can be found in [1] devoted to the analysis of inelastic interactions of 3.5 GeV/c π^--mesons with xenon nuclei. Some characteristic features of these interactions were also pointed out:

(1.1) There exists a class of events not accompanied by the creation of charged $\pi^{\pm}$ and neutral π° mesons, and it accounts for about 12% of the total inelastic π^-Xe cross section.

(1.2) The average multiplicity of fast protons (i.e., those having kinetic energy lying within an interval of 20-400 MeV) in interactions with nonzero number of secondary pions (including neutrals also) is $\langle n_p \rangle = 4$.

(1.3) There exists some part, about 1.2% of π^-Xe collisions, in which proton emission is not accompanied by any secondary pion, here $\langle n_p \rangle = 8$.

A hope for a better understanding of these phenomena would make a clear motivation for any further investigation in this direction using other types of incident particles of similar momentum. This has been done in the present paper using data on inelastic interactions of 4.5 GeV/c protons with emulsion nuclei. Foe details see [2].

The present paper is arranged as follows. In section 2 we review our experimental data and make a systematic comparison between characteristics of process with and without particle creation. Section 3 is devoted to the comparison with the cascade evaporation model. Some investigations are also made within the model itself. In section 4 we draw conclusions and try to build up our picture of the phenomenon studied.

2. EXPERIMENTAL DATA

In a sample of events consisting of 2526 inelastic interactions of 4.5 GeV/c protons with emulsion nuclei all secondary tracks were classified according to usual photoemulsion criteria: shower tracks (s-particles) belong to singly-charged particles with velocity ($\beta>0.7$). The rest of the tracks are called heavy (h-particles). The latter are divided into black tracks (b-particles) having a range in emulsion R less than 3 mm and gray tracks (g-particles) the characteristics of which will be a main topic in our subsequent analysis. In this work we didn't identify the mass and charge of emitted particles. Let us note that our criteria for g-track selection correspond to the proton and pion kinetic energies lying within an interval of 26-400 and 6-60 MeV, respectively. Though a small mixture of pions between g-particles may be present and some shower tracks may belong to knocked-out protons, we make "a standard mass assignment" and, as usual, neglect the above-mentioned possibilities. Indeed, it is not a big mistake because what we are going to do in this section is to make a relative comparison between two groups of events specially selected. But this could have an influence on results of the next section, where a comparison with the model is made, if we have not taken our experimental criteria into account.

Excluding interaction events with s-particle multiplicity $n_s=1$ from our analysis, the total sample is broken into two classes:

<u>class A</u>: events without multiple production of charged relativistic secondaries, i.e., with $n_s=0$.

<u>class B</u>: events with $n_s>1$, i.e., with one or more created relativistic particles.

In what follows we drop the term "relativistic" from "created relativistic particles" having in mind our mass - assignment convention. Thus, a subsequent analysis is completely devoted to a systematic comparison of the characteristics of class A and B events.

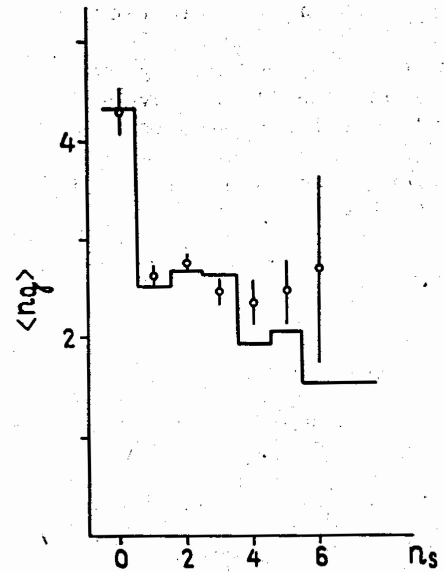

Fig. 1. Regression of n_g on n_s. Circles are our data, histogram - CEM.

Table 1

T_{kin}, GeV	2.2	3.6	6.2	8.7	22.5
A, %	31.8	11.6	4.2	3.5	0.7
$\langle N_h \rangle$	9.87±0.34	9.52±0.42	7.78±0.70	4.58±0.77	5.00±0.97
$\langle n_g \rangle$	—	4.31±0.19	3.11±0.31	—	1.33±0.52

Figure 1 shows the dependence* of the average multiplicity of gray particles $\langle n_g \rangle$ on the multiplicity of shower particles. Excluding point $n_s=0$ for a moment, we observe almost an independent behaviour of the average multiplicities of heavily ionizing particles on the s-particle multiplicity. Point $n_s=0$ singles out itself by two times higher average multiplicities of gray particles. Noting that g-particles consist mainly of protons with kinetic energy from 26 to 400 MeV, we have some analogy to the results of the π^-Xe interaction analysis [1] listed in the preceding section (points (1.1) and (1.2)).

In Table 1 we present a compilation of some characteristics of class A events for proton-emulsion inelastic interactions at various projectile kinetic energies up to the 22,5 GeV [3,4,5]. Decreasing a role of class A events with increasing proton energy can be observed. This behaviour forces $n_s=0$ events for energies higher than 20 GeV up to cosmic ray energies to form no distinguished group of events [6]. Average multiplicities $\langle N_h \rangle$ and $\langle n_g \rangle$ show a behaviour similar to the relative cross section though their decrease is not so steep.

Figure 2 shows the multiplicity distributions of g-particles for classes A and B, respectively. We conclude that there is a marked difference between both distributions: namely, it is worth mentioning a broadening of the n_g-distribution for class A events in comparison with class B. To reveal if

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*In what follows any dependence of this type, i.e., $\langle y \rangle = f(x)$ will be called regression of y on x as it is customary in mathematical statistic.

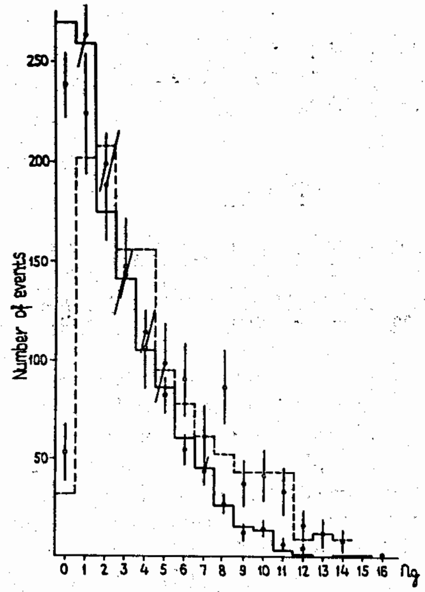


Fig.2. The n_g distribution for the class A (open circles - our data, dashed histogram - CEM) and the class B events (full circles - our data, solid histogram - CEM). Normalization to the same number of particles.

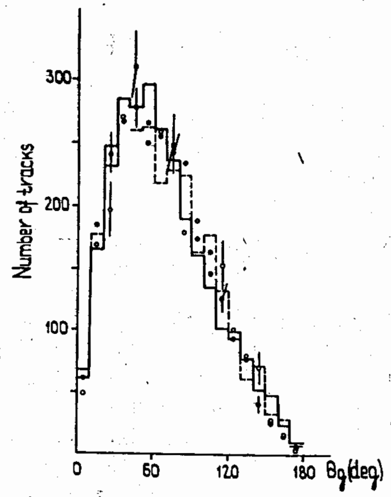


Fig.3. The space angle distribution. Notation here and on the following Figures is that of Fig.2.

Table 2

Class of events	$\langle\theta\rangle$, deg	$\sqrt{D}$, deg	F/B
A	68.9±1.1	37.5±0.9	2.41±0.24
	(68.7)	(38.4)	(2.50)
B	66.6±0.7	36.9±0.5	2.90±0.18
	(66.9)	(37.9)	(2.88)

Table 3

Class of events	$\langle E_g\rangle$, MeV	$\sqrt{D}$, MeV
A	127 ± 4	87 ± 3
	(121)	(99)
B	125 ± 3	95 ± 3
	(121)	(98)

Table 4

Class of events	$\langle n_{LID}\rangle$	$\sqrt{D_{LID}}$	$\langle n_{COL}\rangle$	$\sqrt{D_{COL}}$	$\langle n_{SEC}\rangle$	$\sqrt{D_{SEC}}$
A	1.79	0.94	12.58	9.27	10.79	8.91
B	1.61	0.89	8.62	7.58	7.01	7.21

there are any other characteristics showing such a different behaviour of both classes, we present in Fig.3 a space angle Θ-distribution of gray tracks. Table 2 contains information on average value $\langle\Theta_g\rangle$, standard deviation $\sqrt{Disp_g}$ and forward-

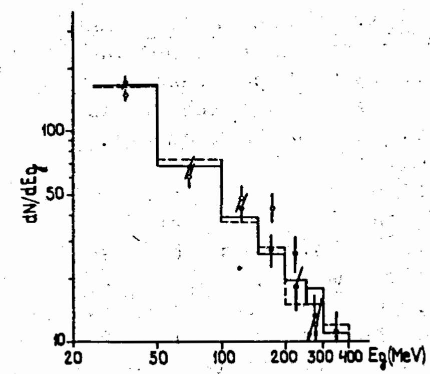
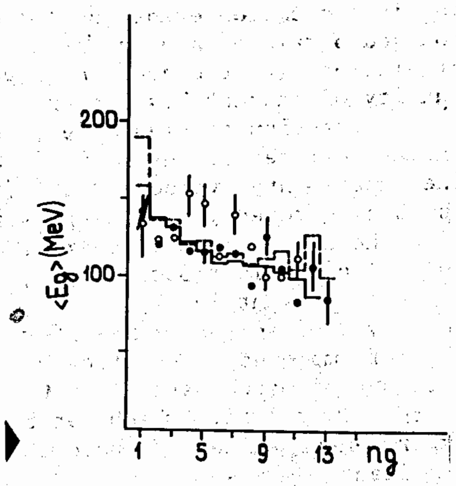


Fig.4. Energy distribution of the gray particles.

Fig.5. Regression of $\langle E_g\rangle$ on n_g.



to-backward ratio F/B values. We observe no major difference in all of the types of angular characteristics presented between class A,B events. Energy spectra of g-particles and values of their first two statistic moments are presented in Fig.4 and Table 3, respectively. Again there is no sign of any marked difference between both classes.

The regression of g-particle's kinetic energy on their multiplicity n_g: $\langle E_g\rangle \sim f(n_g)$ is certain to be a more subtle characteristics then the above single-particle spectra. But comparing spectra of class A and B events on Fig.5, we can hardly drew any conclusion concerning different behaviours of events belonging to class A or B. We can thus summarize:

a) The multiplicity distribution of g-particles for events with $n_s = 0$ differs significantly from the corresponding one for events with $n_s > 1$.

b) We have found no other (neither single-particle nor regression-like) characteristics in which class A events behave differently from class B ones.

3. COMPARISON WITH THE CASCADE EVAPORATION MODEL

Keeping in mind what should be a main goal of our analysis, i.e., to find out processes responsible for a main bulk of $n_s = 0$ events, we have compared all experimental characteristics discussed in the preceding section to cascade evaporation model (CEM) predictions. For comparison we have taken 4879 randomly generated interactions (stars) in nuclear emulsion [2] and present our results in Figs.2-5 and Table 2 and 3. The conclusion which can be drawn from here is that not only multiple-creation events but also events with no creation of charged particles are in satisfactory agreement with the CEM predictions (to the accuracy given by the quantity and (or) quality of characteristics presented).

The fraction of class A events of the total sample of all inelastic interactions is 9% in CEM what is not so far from the experimental value in Table 1 (12%). This value can be further improved if we change slightly some model parameters with the aim to improve overall agreement in shower particle multiplicity distribution, but, of course, at the price of poorer agreement in other characteristics (multiplicities of heavily ionizing particles, for instance). We have made this type of improved calculation and obtained 11.0%, but for the same set of model parameters CEM gives 22% for proton kinetic energy $T = 2.2$ GeV, which can be compared to the Table's 1 experimental value 32%. Here the agreement, though not so excellent, is also not very bad and we conclude, that CEM is capable to describe both a magnitude and energy dependence of relative cross section for $n_s = 0$ events reasonably well.

A subset consisting of 2370 model stars (which can be considered for our purposes as a random selection from total statistics of 4879 stars) carry also information on the number of collisions suffered by the primary particle inside the nucleus n_{LID}, the full number of collisions n_{COL} and the

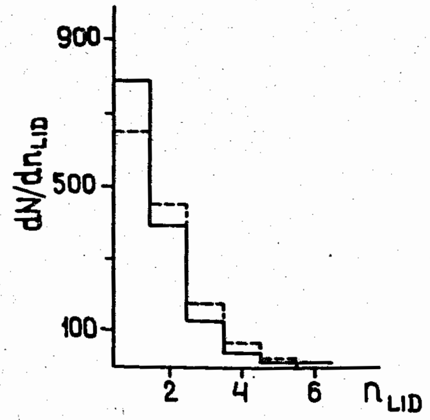


Fig.6. Distribution of the number of collision of the leading particle according to the CEM.

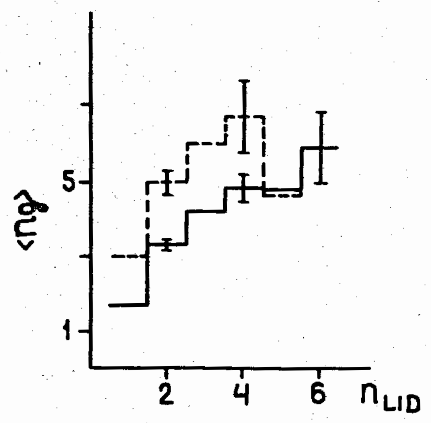


Fig.7. Regression of n_g on the number of collisions of the leading particle in the CEM.

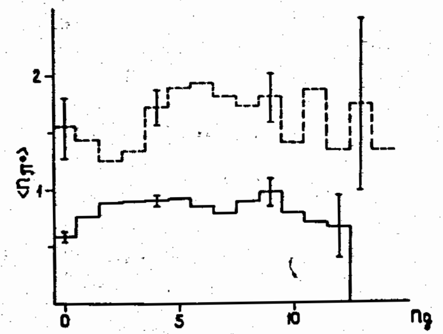


Fig.8. Regression of the multiplicity of neutral pions on n_g in the CEM.

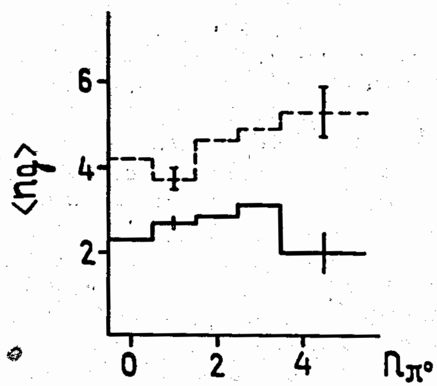


Fig.9. Regression of n_g on the multiplicity of neutral pions.

Table 5

Class of events	$\langle N_n \rangle$	$\langle n_{\pi^0} \rangle$	$\langle T_{LID} \rangle$
A	11.8	1.56	1454
B	8.3	0.79	517

number of secondary particle collisions n_{SEC}. Table 4 presents mean values and standard deviations of these quantities. The distribution of n_{LID} and regression of n_g on n_{LID} for classes A and B are shown in Figs.6 and 7, respectively. From the latter the conclusion could be made that in the mean the number of g-particles in class A is 1.5 times larger than in B at every collision of leading particle. Of course, this fact explains the experimentally observed broadening of the n_g-spectra for $n_s = 0$ events, but it clearly says nothing about what makes a collision act of leading particle to be so peculiar for class A interactions as it is. Inspection of the Table 4 data shows that $\langle n_{LID} \rangle_A$ is only about 10% higher than $\langle n_{LID} \rangle_B$ whereas the corresponding quantities for the number of collisions suffered by secondaries differ by more than 50%. Thus, we conclude that the main clue to understand process of hadron nucleus interaction without multiple particle production must lie (within the CEM bounds, of course) in understanding characteristics of neutral particles. These are presented in Table 5. Regressions of the multiplicity of neutral pions n_{π^0} on n_g and their inverse are shown in Figs.8 and 9, respectively. We observe that these quantities are weakly correlated for both classes of events, and this makes neutral pions not to be very responsible for the observed difference in n_g-distributions.

What has now remained at our disposal are neutrons. Their average multiplicity $<N_n>$ is 1.5 times higher for $n_s=0$ events, and interactions on heavy emulsion nuclei Ag, Br are their main source (for the fraction of events on AgBr the CEM gives 81% and 70% for classes A and B, respectively). Being well aware of the role played by charge exchange of leading particle at projectile momenta of several GeV, in Table 5 we present the average kinetic energy of the fastest neutron from a given star (let us call it leading neutron) $<T_{LID}>$. A close inspection clearly confirms our expectations; moreover, a group of events with $T_{LID} < 400$ MeV and $N_n < 10$ composes only 0.5% of class A events and 33% of class B.

These facts allow us to state the following picture of proton-nucleus interactions without multiple production of relativistic charged particles: in the first or more probably (because of elementary process energy dependence) in the second (possibly in the third) collision the incident proton loses its charge turning itself to the neutron. Our experimental constraint (i.e., $n_s=0$) forces it not to gain charge in any possible subsequent intranuclear collision unless its final energy is very small ($T < 400$ MeV), what seems to be highly improbable using the cascade mechanism only. Created charged pions must be absorbed inside the nucleus or must escape out with a very small (<60 MeV) kinetic energy.

4. CONCLUSIONS

On the basis of our analysis of experimental data and their comparison to the CEM predictions we can draw the following conclusions:

1. a) There exist approximately 12% of inelastic $p+Em$ interactions at a 4.5 GeV/c incident momentum, where the emission of heavily ionizing particles is not accompanied by any shower particle ($n_s=0$).

   b) In events of this type the average multiplicity of g-particles is almost two times higher than in the remaining events.

   c) The shape of the n_g-distribution differs markedly for these events being broader than for multiple production events ($n_s > 1$).

   d) We have not found any noticeable difference in angular and energy characteristics of these groups.

2. The role played by the $n_s=0$ class of events decreases with increasing primary proton energy.

3. a) General features of the process which builds up events of this type at our energies can be satisfactorily described by the CEM.

   b) A deeper inspection into the CEM confirms the picture in which $n_s=0$ events are mainly build up from the interactions when the incident proton loses its charge inside the nucleus.

   c) The events not accompanied by multiple creation are mainly generated on heavy nuclei, and thus a substantial role in energy balance is played by neutrons.

ACKNOWLEDGEMENTS

We are grateful to the members of Alma-Ata - Bucharest - Dubna - Koshice - Leningrad - Moscow - Tashkent - Ulan-Bator Collaboration for providing us with their data on proton-emulsion interactions at 4.5 GeV/c and especially to V.A.Pljuschev, Z.I.Solovjeva and V.G. Bogdanov from Leningrad Khlopin Institute which have made available to us their unpublished energy spectra of gray particles. We acknowledge a work of B.F.Kostenko in Monte Carlo Generation of events from Cascade evaporation model and also some useful discussion about CEM which he has with us. The authors sincerely thank K.G.Gulamov for encouragement, helpfull suggestions at all stages of this work and critical reading of manuscript and to B.P.Bannik for discussion and collaboration at the early stages of this work. And, at least but not at last, we are grateful to K.D.Tolstov for constant support and encouragement.

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Received by Publishing Department
on June 26 1981.