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INELASTIC INTERACTIONS OF 4.5 GeV/c PROTONS WITH EMULSION NUCLEI NOT ACCOMPANIED BY RELATIVISTIC CHARGED PARTICLES

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Experimental results on proton-emulsion interactions without charged particles creation are presented and analysed. The role of this type of events through not negligible at energies of several GeV diminishes rapidly with increasing projectile energy. Except for a broader multiplicity distribution of gray particles all other characteristics are similar to those of multiple production. A comparison with the cascade evaporation model has been made and a reasonable agreement has been found.

НЕУПРУГИЕ ВЗАИМОДЕЙСТВИЯ ПРОТОНОВ С ЭНЕРГИЕЙ 4,5 ГэВ/с С ЯДЕРНОЙ ЭМУЛЬСИЕЙ БЕЗ РОЖДЕНИЯ РЕЛЯТИВИСТСКИХ ЗАРЯЖЕННЫХ ЧАСТИЦ

В работе приведены и проанализированы экспериментальные результаты по изучению взаимодействия протонов с эмульсией без рождения заряженных частиц. Показано, что роль событий этого типа, хотя и непренебрежима при энергиях порядка нескольких ГэВ, с увеличением энергии налетающей частицы быстро падает. Все характеристики процесса близки к случаю множественного рождения, за исключением более широкого распределения по множественности серых частиц. Проведено сравнение данных с каскадно-испарительной моделью и получено удовлетворительное сограсие с последней.

I. INTRODUCTION

At present it is widely recognized that the study of multiple production of 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 interest for particle physics, mainly because it offers important and unique information on the structure

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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 though it is of a 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 the present paper we have tried to follow 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 the 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:

(I.1) There exist a class of events not accompanied by the creation of charged $\pi^\pm$ and neutral π^0 mesons, which accounts for about 12 % of the total inelastic π^- Xe cross section.

(I.2) The average multiplicity of fast protons (i.e. those having a kinetic energy within the interval of 20—400 MeV) in interactions with a nonzero number of secondary pions (including neutrals also) is $\langle n_p \rangle = 4$.

(I.3) There exists some preceding collisions, about 1.2% of π^-Xe ones in which proton emission is not accompanied by any secondary pion, here $\langle n_p \rangle = 8$.

A better understanding of these phenomena would motivate any further investigation in this field using other types of incident particles of a similar momentum: That is why in the present paper we apply data on inelastic interactions of 4.5 GeV/c protons with emulsion nuclei. For details see [2].

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

II. 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 other 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 the present work we did not identify the mass and charge of the emitted particles. Let us remark 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. Thouth 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, this is not a big mistake since we are simply going to make in this section a relative comparison between two groups of events specially selected. This could, of course, have an influence of the results of the next section, where a comparison with the model is made if we have not taken our experimental criteria into account.

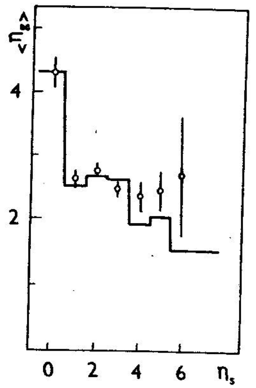

Fig. 1. Regression of n_g on n_s. The circles are our data, the histogram — CEM.

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

Class A: events without multiple production of charged relativistic secondaries, i.e. with $n_s = 0$.

Class B: 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.

Figure 1 shows the dependence1) 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 an almost independent behaviour of the average multiplicities of heavily ionising particles on the s-particles multiplicity. Point $n_s = 0$ is outstanding because of twice as many average multiplicities of gray particles. Nothing that g-particles consist mainly of protons with a kinetic energy from 26 to 400 MeV, we

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1) 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 statistics.

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
$\langle N_n \rangle$	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

have an analogy to the results of the π^- Xe interactions analysis [1] listed in the preceding section (points (I.1) and (I.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]. A diminishing of the 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 $\langle N_n \rangle$ and $\langle n_g \rangle$ show a behaviour similar to the relative cross section through their decrease is not so steep.

Figure 2 shows the multiplicity distributions of g-particles for classes A and B. We conclude that there is a marked difference between the two distributions: there is namely a broadening in the n_g-distribution for class A events in comparison with those of class B. To reveal further characteristics showing this different behaviour of the two classes, we present in Fig. 3 a space-angle Q-distribution of gray tracks. Table 2 contains information on the average value $\langle \Theta_g \rangle$, standard deviation $\sqrt{Disp_g}$ and forward-to-backward ratio F/B values. We observe no major difference in all the types of angular characteristics presented between class A and class B events. Energy spectra of g-particles and values of their first two statistic momenta are presented in Fig. 4 and Table 3, respectively. Again there is no marked difference between the two classes.

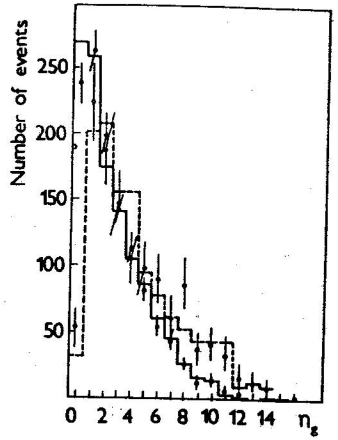

Fig. 2. The n_g distribution for the class A (open circles — our data, dashed histogram — CEM) and the class B events (full circles — our data, solid histogram — CEM). Normalization to the same number of particles.

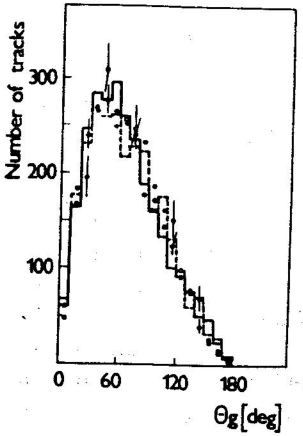

Fig. 3. The space angle distribution. Notation here and in the following Figures is that of Fig. 2.

Table 2

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

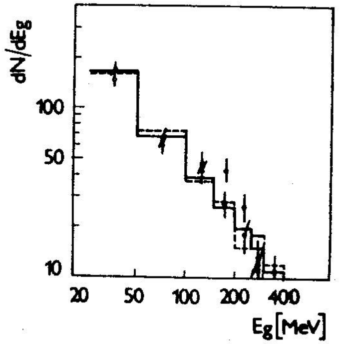

Fig. 4. Energy distribution of the gray particles.

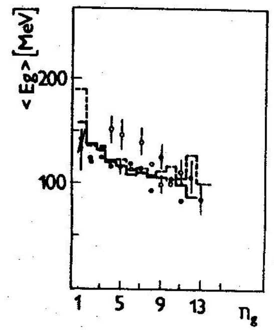

Fig. 5. Regression of ⟨E⟩ on n_g.

The regression of the g-particles kinetic energy on their multiplicity $n_g : \langle E_g \rangle \sim f(n_g)$ is certainly a more subtle characteristic than the above single-particle spectra. But comparing spectra of class A and class B events in Fig. 5, we can hardly draw only any conclusion concerning the different behaviour of events belonging to class A or class 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.

III. COMPARISON WITH THE CASCADE EVAPORATION MODEL

Keeping in mind the main aim of the analysis, i.e. to find out processes responsible for the main bulk of $n_s = 0$ events, we have compared all experimental

Table 3

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

characteristics discussed in the proceding section with the 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 Tables 2 and 3. The conclusion which can be drawn from the above is that not only multiple-creation events but also events with no creation of charged particles are in a satisfactory agreement with the CEM predictions (up the accuracy given by the quantity and/or quality of the characteristics presented).

The fraction of class A events of the total sample of all inelastic interactions is 9% in CEM, which does not differ greatly 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 an overall agreement in shower particle multiplicity distribution, but, of course, at the price of a poorer agreement in other characteristics (multiplicities of heavily ionizing particles, for instance). We have chosen this type of improved calculation and obtained 11.0%, but for the same set of model parameters CEM gives 22% for the proton kinetic energy $T=2.2$ GeV, which can be compared to the experimental value 32% in Table 1. Here the agreement, though not so excellent, is not too bad either and we conclude that CEM is capable to describe both a magnitude and energy dependence of the relative cross section for $n_s=0$ events reasonably well.

A subset consisting of 2370 model stars (which can be considered for our purpose as a random selection from the total statistics of 4879 stars) carries 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 number of secondary particle collisions n_{SEC}. Table 4 presents the mean value and standard deviations of these quatities. 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-praticles in class A is 1.5 times larger than in B at every collision of the 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 the leading particle so pecular for class A interactions as it is. Inspection of Table 4 data shows

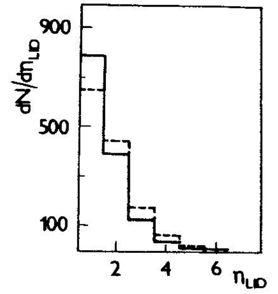

Fig. 6. Distribution of the number of collisions the leading particle according to the CEM.

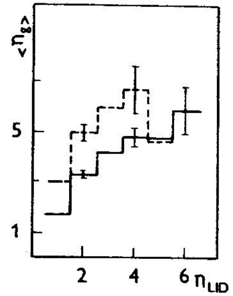

Fig. 7. Regression of n_g on the number of collisions of the leading particle in the CEM.

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 the process of the hadron nucleus interaction without multiple particle production must be (within the CEM bounds, of course) in understanding the 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 does not make neutral pions conspiciously responsible for the observed difference in n_g-distributions.

What has now remained at our disposal are neutrons. Their average multiplicity $\langle N_n \rangle$ 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 the charge exchange of the leading particle at projectile momenta of several GeV, we present in Table 5 the average kinetic energy of the fastest neutron from a given star (let us call it the leading neutron) $\langle T_{LID} \rangle$. A close inspection clearly confirms our expectations; moreover, a group of events with $T_{LID}<400$ MeV and $N_n<10$ constitutes only 0.5% of class A events and 33% of class B.

These facts lead to the following conception of the 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 into

Table 5

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

a neutron. Our experimental constraint (i.e. $n_s = 0$) forces is not to gain a charge in any possible subsequent intranuclear collisions unless its final energy is very small ($T < 400$ MeV), which seems to be highly improbable by using the cascade mechanism only. Created charged pions must be absorbed inside the nucleus or must escape with a very small (< 60 MeV) kinetic energy.

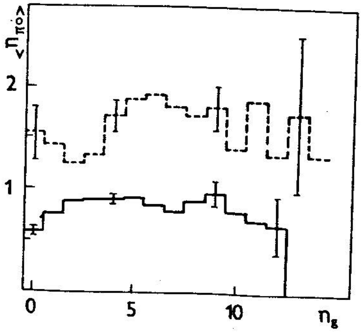

Fig. 8. Regression of the multiplicity of neutral pions on n_g in the CEM.

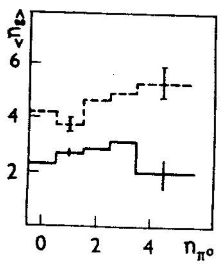

Fig. 9. Regression of n_g on the multiplicity of neutral pions.

IV. 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 twice as hight as in the remaining events.

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

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

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

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

b) A deeper insight into the CEM confirms the picture where the $n_s = 0$ events are build up mainly from interactions where 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.

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