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BACKWARD PARTICLE PRODUCTION BY PROTONS AND ^{12}C NUCLEI IN EMULSION AT MOMENTA OF 4.5 GeV/c/A

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1. INTRODUCTION

In the last few years the backward production of particles off nuclei has attracted much attention both from the experimental and the theoretical side of the problem. Though some progress in understanding this phenomenon has been made on the experimental side, the field of theoretical speculations remains, however, to be a diverse one [1-5].

Of course, this is due to the scarcity of experimental data, on the one hand, also to the bias which takes place in data analyses (or from the purely "collectivistic" or purely "single-particle" points of view), on the other hand.

One of the principal objectives of this paper, though may be too ambitious, is to discover whether or not the mechanism of particle emission into the backward hemisphere is significantly different from that into the forward hemisphere. This can also help us to clear up some puzzles connected with the role of collective phenomena (production off clusters, etc.) in the backward emission of particles from nuclear targets. On the other hand, we feel that the phenomenon of limiting fragmentation, which starts at incident energies close to that of ours [6], must show itself at first in that region of phase space, which is most safe from the mingling of contributions from the target and projectile fragmentation regions. This is of course the backward hemisphere in the laboratory reference frame, where this occurs first and where a great similarity of particle characteristics is to be expected independently of the incident nucleus.

The present paper is devoted to the study of various characteristics of events giving rise to the pions or protons emerging with $\Theta_{Lab} > 90°$ (i.e., in the backward direction relative to the incomming particle). The latter being proton of ^{12}C nucleus with a primary momentum of 4.5 GeV/c/nucleon in our case, which interacts with nuclei of a photographic emulsion. For the case of p+Em interaction, calculations by a cascade evaporation model (CEM) are presented.

2. EXPERIMENTAL PROCEDURES

Two stacks of BR-2 photographic emulsions were exposed to a proton and ^{12}C beam with a momentum of 4.5 GeV/c/nucleon at the Dubna synchrophasotron in 1978 and 1975, respectively. Data studied in the present work consist of 2526 and 1001 p+Em and ^{12}C+Em inelastic interactions, respectively, which were found by the along-the-track scanning method. The main characteristics of these interactions, selection rules and other details concerning the experimental procedure have been published elsewhere /7-10/.

Here we restrict ourselves to the usual photoemulsion classification of secondary tracks: shower tracks (s -particles) which belong to singly-charged relativistic particles having momentum over mass ratio $p/mc>1$, i.e., $\beta > 0.7$ as obtained from ionization measurements. The remaining tracks are called h - tracks and are due to heavily ionizing particles. The latter are divided into black tracks (b -particles) having a range in emulsion $R \leq 3$ mm and grey tracks (g -particles) with relative ionization $g/G > 1.4$ and $R > 3$ mm (corresponding velocity of singly-charged particle $0.7 > \beta > 0.3$, i.e., for proton $400 > T_p > 26$ MeV. Here G is ionization as measured on the track of minimum ionizing particle (primary proton and singly-charged fragment of the projectile in the case of p+Em and ^{12}C+Em interactions, respectively). Let us stress here that for the case of ^{12}C+Em interactions projectile fragments (spectators) were carefully excluded from the above classification scheme /9,10/.

3. DATA ANALYSIS

3.1. Angular Characteristics of s- and g-Tracks

In order to show some general feature of the backward production of particles and also to make a connection of our results with those obtained in inclusive experiments /1,11-14/ (predominantly electronic ones, of course), we begin to discuss our data by presenting angular spectra in the backward hemisphere. The differential angular distribution of g -particles (normalized to the same number of tracks) shown in Fig.1 displays clearly enough the onset of limiting fragmentation of the target nucleus at our energies. We would like to stress here that this behavior is in complete disagreement with that in the forward hemisphere and also (because of the well-known exponential fall-off in $\cos\Theta_g$ -variable) with the general picture as given by unrestricted angular spectra of grey particles /8,10/.

The behaviour very similar to that noted for g -particles reveals itself in the backward angular integral distribution of shower particles (Fig.2).

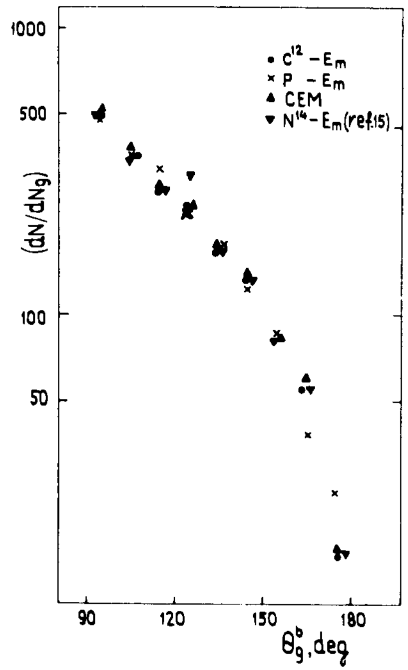

Fig.1

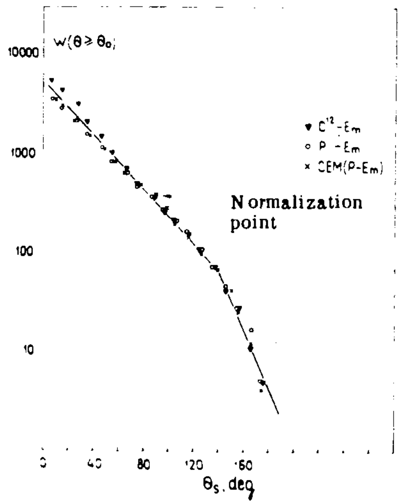

Fig.2

3.2. Multiplicities of s- and g-Particles

In this subsection we would like to compare multiplicities of various types of particles in the forward and backward regions to each other and also to compare the latter with changing projectile and/or target nucleus mass.

Table 1

Reaction	$\langle n_s \rangle^f$	$\langle n_s \rangle^b$	$\langle N_g \rangle^f$	$\langle N_g \rangle^b$	$\langle N_h \rangle^b$
C^{12}+Em	7.11±0.2	0.34±0.02	4.49±0.19	1.38±0.07	3.30±0.11
P+Em	1.51±0.02	0.11±0.01	2.05±0.04	0.74±0.02	2.39±0.05
P+Em(CEM)	1.63	0.12	1.98	0.72	2.22
P + Ta*	0.45±0.02	—	—	0.64±0.03	—
C^{12} + Ta*	3.39±0.02	—	—	2.08±0.07	—

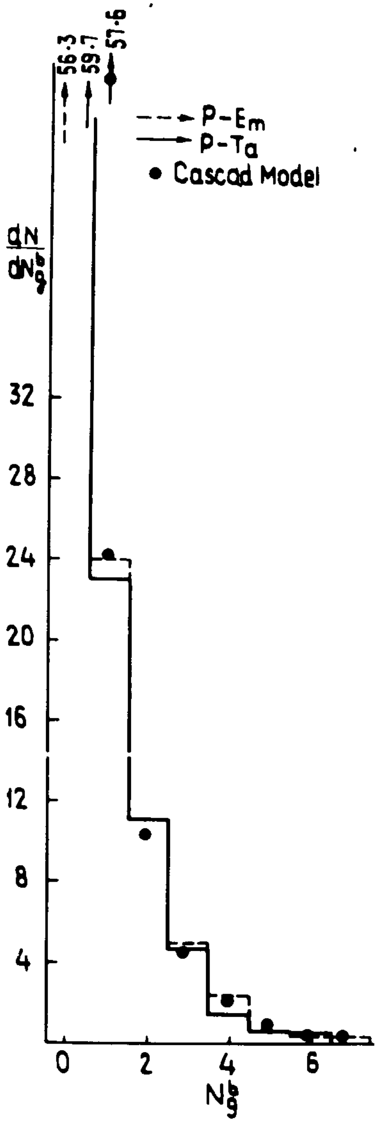

Fig.3

All available data are presented in Table 1 and Fig.3. In addition to the photoemulsion data used until now, data from the propane bubble chamber/16/ having ^{181}Ta nucleus as an internal target, are also presented.

We observe that the multiplicity distributions of grey particles (resp. fast protons) are very similar for p+Em and p+Ta interactions. A small difference could be well accounted for by a 11% contamination/17/ of grey particles by pions in photoemulsion data excluded otherwise from a bubble-chamber sample. Changing projectile nucleus from p to ^{12}C leads to a noticeable enrichment of the distribution by high-multiplicity events (we can judge it from the increase of $\langle N_g^b \rangle$ supposing the N_g^b-distribution for ^{12}C interactions to be a similar monotonously falling function as in the proton case). The same being also true if we increase the target mass while fixing that of projectile to the ^{12}C-nucleus mass. Assuming that the average energy of g-particles emitted into the backward hemisphere does not differ significantly for all the cases considered, the broadening of the N_g^b distribution has to mean an increase of the energy transferred to the backward target fragmentation region. At the same time, a limitation on overall available energy (for the case of proton projectile) transferred to the backward region can be a prominent reason for relative stability of the N_g^b-spectra with changing the target mass.

The average multiplicities of shower and grey particles (Table 1) show not only a predominant probability of the forward emission over the backward one, but also a slightly different dependence of the average multiplicities on the mass number of the projectile in both regions, $\langle N_i^{f,b} \rangle \sim A_p^{\alpha_i^{f,b}}$

$\alpha_g^f \approx 1/3, \quad \alpha_g^b \approx 1/4$ and $\alpha_s^f \approx 2/3, \quad \alpha_s^b \approx 0.45.$

This, together with the said above, means that the process of particle multiplication due to the increase of available energy prevails in the region directed along the projectile motion, while in the backward region it is relatively damped. The A_p-dependence of $\langle N_s^f \rangle$ can suggest, on the other hand, that a prominent role in the process of particle multiplication should be prescribed to the increase of the projectile geometrical cross section.

It is interesting to note that the multiplication of s-particles in the backward hemisphere may not occur in the same way as in the forward one. Indeed, taking the average number of interacting nucleons $A_{^{12}C}^{int} \approx 5$ instead of A_{proj}/10/, then $R_s^b = \langle N_s^b \rangle_{^{12}C} / \langle N_s^b \rangle_p = 3.0 \pm 0.3 \approx (A_{^{12}C}^{int}/A_p)^{2/3} \approx 2.9$. As a simple check that this agreement is not accidental, we can compare the backward multiplicity ratio for the case, when probably all twelve carbon nucleons have interacted (by triggering on $N_h > 28$ events), with nonperipheral p+AgBr interactions ($N_h > 6$). Here $R_s^b = 5.0 \pm 0.3$ is in good agreement with the geometrical prediction $(12)^{2/3} \approx 5.2$.

If we try to interpret these geometrical cross sections as interaction probabilities, then the following picture can be possible: while $\langle N_s^f \rangle$ depends only on the probability that the incident nucleus interacts with the target, $\langle N_s^b \rangle$ is proportional to the probability that only the wounded part of the projectile interacts again in secondary collisions.

3.3. Multiplicity Correlations

As we have stressed earlier, the backward hemisphere is intimately connected with the target fragmentation region, i.e., with that part of phase space where all single particle characteristics are most safe from being dependent on the projectile. Indeed, the rapidity of the projectiles considered is $y_p = 2.26$ and, because of this, for every backward particle rapidity y^b the following unequality is fulfilled: $|y_p - y^b| > 2$, what is nothing but sufficient conditions for the onset of limiting fragmentation/6/.

If the limiting fragmentation really starts to play an important role at our energies, then the only quantity by which projectile may communicate with the target fragmentation region is the energy transferred. In photoemulsion studies it is customary to take the multiplicity of heavily ionizing particles N_h as an indirect measure of this quantity.

One example of the correlation dependence on N_h is shown in Table 2, where $(F/B)_i = f(N_h)$, i=s and g is plotted.

Integrated over all N_h, this quantity in p+Em and ^{12}C+Em interactions equals 2.77±0.07 and 3.25±0.09 for grey particles and 14±1 and 21±1 for shower particles, respectively.

Table 2

N_h	P-Em		C^{12}-Em	
	$(F/B)_s$	$(F/B)_g$	$(F/B)_s$	$(F/B)_g$
1-3	25±4 (23)	3.9±0.4 (4.3)	53±13	4.6±0.8
4-6	17±2 (16)	4.6±0.4 (3.2)	33±5	3.7±0.4
7-9	13±2 (9)	2.8±0.2 (2.6)	31±6	3.6±0.4
10-13	9.8±1.6 (8.5)	2.7±0.2 (2.7)	20±4	4.3±0.5
14-16	5.6±1.0 (6.3)	2.7±0.2 (2.5)	17±4	2.5±0.3
17-19	6.4±1.5 (6.3)	2.3±0.2 (2.3)	28±7	3.0±0.3
20-24	5.6±1.3 (4.9)	2.3±0.2 (2.6)	20±3	3.3±0.3
25-28	3.0±1.3 (3.0)	2.3±0.3 (1.9)	17±1	3.1±0.1
>28	—	—	13±1	3.3±0.1

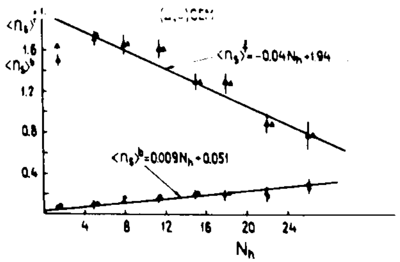

Fig.4

The data of Table 2 show that:

1) Anisotropy of the angular distributions considered decreases with increasing N_h (more rapidly for s-than for g-particles).

2) For p+Em interactions $(F/B)_g$ reaches for $N_h>16$ a plateau, the value of which is within the experimental error equal to that as given for all p+Em interactions (N_h-integrated) for the interval of incident energies $E_p=(20\div400)$ GeV.

3) For ^{12}C+Em interactions $(F/B)_g$ also shows a possible limiting behaviour in the region $N_h>16$. A higher value of "the plateau" can be due to the above fact that AgBr nucleus is too small to excite all internal degrees of freedom of the projectile.

We have constructed regressions of $N^f_{s,g}$ and $N^b_{s,g}$ on N_h. They all exhibit a positive correlation which can be, with a goc accuracy, approximated by a straight line (not shown here). The only exception from this behaviour represents correlation $\langle N^f_s\rangle_p = f(N_h)$ (Fig.4) which is negative (though a linear one again).

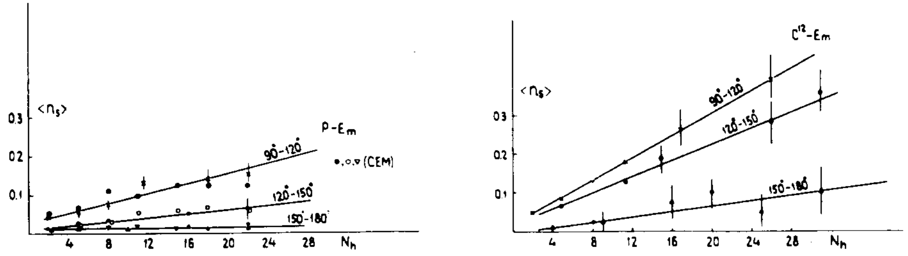

Fig.5

This behaviour but for the total average multiplicity $\langle N_s\rangle$ (of which, however, $\langle N^f_s\rangle$ makes about 93%) has been noted by us previously [7,8] and interpreted as a manifestation of prevailing of shower particle absorption in the target nucleus over the processes of meson creation and knock-out of relativistic protons.

The fact that the backward region is free from this effect is most easily seen from the regression of N^b_s on N_h plotted in Fig.4. A more close look at this is given by Fig.5, where regressions of N_s on N_h are presented in three different backward angular subregions. We observe that a positive correlation between $\langle N_s\rangle$ and N_h decreases with increasing the emission angle of s-particles showing an important influence of nuclear thickness on the absorption of relativistic particles. We noted that a decrease of nuclear density in the region, just passed by the fastest relativistic particles migrating to the forward hemisphere (trailing effect), could be also of some importance here.

All what has been said about the regressions of $N^{f,b}_s$ on N_h remains to be true also with respect to regressions on the N^b_h - multiplicity of heavily ionizing particles emitted to the backward hemisphere (Figs.6 and 7). A flattening and/or a decrease of $\langle N^b_s\rangle$ at high N^b_h values may be due to a limitation of overall energy available in p+Em interactions at our energy. This is also confirmed by a negative correlation between $\langle N^f_s\rangle$ and N^b_s (Fig.8).

In Table 3 we have collected for different N_h-groups the values of coefficient α^d_i, $\langle N^d_i\rangle \sim A_p^{\alpha^d_i}$, i=s,g and d=f,b We observe that:

1) A projectile-mass dependence of the average multiplicities is more pronounced for nonperipheral ($N_h>13$) interactions with AgBr nuclei than for the remainder ($N_h\leq13$).

2) A value of α^p_s allow us, within experimental errors, to conclude that in high N_h interactions a shadowing between different projectile nucleons is absent.

3) Supposing that N_h is an increasing function of the number of wounded projectile nucleons, a change of α_s^b with N_h is consistent with our previous conclusion that backward shower particle production is possibly due to the rescatterings of wounded nucleons only.

4) A noticeable dependence of $N_g^{f,b}$ on N_h is seen only at high enough values of energy transfer (i.e., at high N_h values) underlining again the importance of gradual deliberation of internal degrees of freedom of the projectile during its passage through the nuclear target.

Table 3

N_h	α_s^f	α_s^b	α_g^f	α_g^b
1 – 6	0.41±0.05	0.15±0.03	–.03±0.02	0.02±0.02
7 – 13	0.53±0.10	0.24±0.05	0.05±0.03	–0.08±0.02
14 – 24	0.92±0.32	0.40±0.09	0.18±0.04	0.10±0.04
>24	1.22±0.42	0.46±0.10	0.29±0.09	0.17±0.07

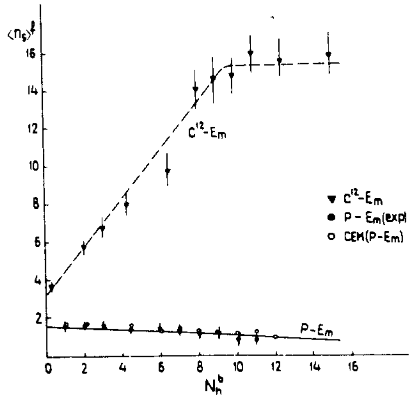

Fig.6

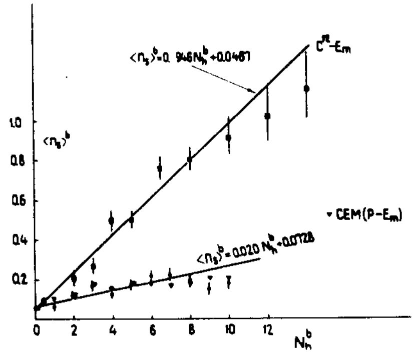

Fig.7

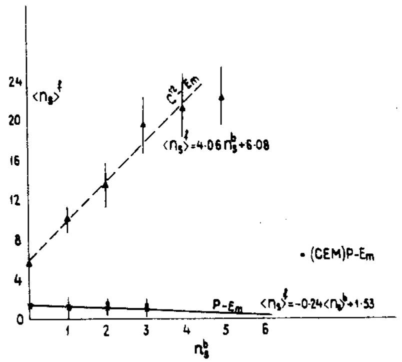

Fig.8

Closing this subsection, we note that the regressions of $N_g^{f,b}$ on N_h^b are not very different from those on N_h ; only at high values a flattening occurs (earlier for p+Em than for ^{12}C+Em interactions) having possibly a similar reason as that for $\langle N_s^b\rangle$.

4. SOME COMMENTS ON THE MODELS OF BACKWARD PRODUCTION OFF NUCLEI

Throughout the last section we have made neither explicit references to the existing models of nuclear interactions at high energies nor to any special ones aiming to describe backward production only. Time has come, however, and we feel that a few remarks are necessary though some data speak for themselves.

The property of limiting fragmentation /6/, as exhibited by the angular spectra os shower and grey particles emitted into the backward hemisphere in Sec.3.1 can suggest that some sort of cooperative interaction of target nucleons with the projectile is needed, but the properties of multiplicities and their correlations, as discussed in Secs.3.2 and 3.3, seem to contradict such a point of view. In fact, a large amount of properties carried by multiplicity correlations in the backward hemisphere is also shared by those in the forward hemisphere. This is more clearly seen if we come from p+Em to ^{12}C+Em interactions. In the latter case, excess in available energy is not simply transformed to a bigger excitation of the target but throughout a successive deliberation in multiple rescattering which results in a positive correlation between s- and h-particle multiplicities in both hemispheres.

Coming to the class of models designed specially to describe the emission of particles into the region forbidden in elementary nucleon-nucleon (NN) collisions, we observe that in the sample studied here there is a large fraction of events containing at least one grey track in the backward direction in addition to a shower particle going into the forward hemisphere, and it is equal to (43.7±1.4)% and (34.4±0.8)% for p+Em and ^{12}C+Em interactions, respectively. We see that this fraction is a decreasing function of the projectile mass number. This leads us to a conclusion close to the one, made by L.S.Schroeder and collaborators /13-15/, that a simple quasi-elastic process NN→NN, as suggested by Frankel /19,20/, is not a dominant mechanism also at our energies*.

There are also other models /2/ falling to this class. Some of them have been analyzed in ref. /21/. There it has been shown that multiplicity correlations do not reveal effects which can be expected on the basis of these models.

* Making this conclusion, we have in fact neglected a contribution of pions to N_g^b, supposing every backward grey track to be that of proton. There are, however, good indications that this contribution to N_g^b is an increasing function of A_p, and our conclusions remains to be true.

The cascade evaporation model (CEM)[22,23], as a representative of a general class of models which reduce the dynamics of nuclear collisions to a more basic NN interaction, is also probably the most adequate model at our energies, mainly because of its wide predictive power. In fact, data on p+Em and ^{12}C+Em interactions, which make up our sample, were compared separately with two versions of CEM[8,10], and agreement was found to be in general quite satisfactory. Discrepancies were the most serious ones in the angular spectra of relativistic particles.

In the case of p+Em interactions a disagreement was observed in the projectile fragmentation region, while in the target region a good agreement was found. For ^{12}C+Em interactions, to the contrary, discrepancies were the most serious ones in the backward hemisphere, where CEM overestimates the $d\sigma/d\cos\Theta_s$-distribution roughly by an order of magnitude. To explain this, two hypotheses were put forward, and namely: the characteristics of elementary NN collisions were bad in CEM for p+Em, and CEM produces overcascading for ^{12}C+Em interactions.

In the present work we have systematically compared data on p+Em interactions with CEM (see Figs.-18 and Table 2), and we can conclude that the agreement in all characteristics presented is very good. If there is any disagreement, it originates in the forward hemisphere and can be explained as above (see the values of (F/B) g for $N_h < 7$ in Table 2). This is hardly surprising if we take into account the fact mentioned before that the target fragmentation region is just the place where the CEM of p+A interactions works possibly because bad imput NN characteristics are completely "forgotten" in the course of intranuclear collisions.

Another question is, of course, why it reproduces also angular distributions of s- and g-particles in the backward hemisphere for the case of ^{12}C+Em interactions. In other words, if limiting fragmentation is the property inherent to the CEM of p+A interactions, why it is not so also for the CEM of A+A interactions, as can be seen from the disagreement in angular spectra of s-particles when the interaction mechanism should be the same in both cases. A possible answer to this may be simple: the CEM of p+A interactions is also not very good in this respect, but because of a low multiplicity of created particles (mesons, mainly) the effect of their own cascading is too small to distore angular spectra appreciably.

Thus, better care must be taken in the CEM of the suppression of interactions of created particles (perhaps, by taking into account resonance production, etc.) if it aims to give a full picture of limiting fragmentation.

5. CONCLUSIONS

The purpose of this paper was to study the backward emission of particles in the interactions of protons and light nuclei (^{12}C) with photographic emulsion nuclei at projectile rapidity y_p=2.26. Using our analysis of experimental data and their partial comparison to the cascade evaporation model of p+A interactions, we can draw the following conclusions:

1. The angular spectra of shower and grey particles emitted into the backward hemisphere are independent of the projectile used (p or ^{12}C) in accordance with the limiting fragmentation hypothesis when applied to nuclei[6].

2. The multiplicity distribution of grey particles emitted into the backward hemisphere is stable with changing the target nucleus (AgBr to Ta) for proton projectile, but not for ^{12}C - projectile where a broadening with increasing target mass number is observed in the N_g^b distribution.

3. The average multiplicities of s- and g-particles in the backward hemisphere have a weaker dependence on the mass number of the projectile than the forward multiplicities. The same being generally true also for multiparticle correlations between these two types of particles and the N_h-multiplicity of heavily ionizing particles.

4. There is a strong correlation between the number of wounded projectile nucleons and the backward s-particle multiplicity.

5. The ratio F/B for the g-particles from p+Em interactions approaches a constant value for $N_h > 16$, which is the same as for p+Em interactions for energies $E \sim 20$ GeV.

6. All regressions of the type $N_{s,g}^{f,b}$ on N_h or on N_h^b are positive and linear with the only exception for N_s^f in p+Em interactions, where the regression is negative.

7. A comparison with the CEM of p+A interactions has shown a good agreement in the target fragmentation region for p+Em interactions.

8. The CEM of A+A interactions is unable to reproduce the phenomenon of limiting fragmentation unless it takes a better care of the suppression of interactions of created particles.

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Испускание частиц назад во взаимодействиях протонов и ядер углерода с фотоэмульсией при импульсе 4,5 ГэВ/c/A

Представлены и проанализированы данные по взаимодействиям протонов и ядер углерода с фотоэмульсией, сопровождаемым испусканием частиц назад. Угловые спектры как серых, так и ливневых частиц, испущенных в заднюю полусферу, не зависят от снаряда. Средние множественности частиц в этой области обладают более слабой зависимостью от ядра снаряда, чем множественности в передней полусфере и для ливневых частиц сильно коррелированы с числом провзаимодействовавших нуклонов снаряда. Сравнение с каскадно-испарительной моделью показало хорошее согласие для p+A, но не для A+A взаимодействий.

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Backward Particle Production by Proton and ^{12}C Nuclei in Emulsion at Momenta of 4.5 GeV/c/A

Experimental results on proton- and carbon-emulsion interactions accompanied by the backward emission of particles are presented and analysed. Angular spectra both of grey and shower particles are projectile independent in the backward region, their average multiplicities in the backward hemisphere have a weaker dependence on the projectile than the forward multiplicities. Backward s-particle multiplicity is strongly correlated to the number of wounded projectile nucleons. A comparison to the cascade evaporation model has shown a reasonable agreement in the target fragmentation region for p+A but not for A+A interaction.

The investigation has been performed at the Laboratory of High Energies, JINR.

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