СООБЩЕНИЯ
ОБЪЕДИНЕННОГО
ИНСТИТУТА
ЯДЕРНЫХ
ИССЛЕДОВАНИЙ

Дубна

E1-97-178

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ON THE POSSIBILITY OF EXPERIMENTAL INVESTIGATION OF EXTREME STATES OF NUCLEAR MATTER. THE INVARIANT INCLUSIVE SPECTRA OF SECONDARY PARTICLES PRODUCTION IN π^-, p, d, ^{4}He, ^{12}C + C INTERACTIONS

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1997

1 Introduction

The search and study of nuclear matter under the extreme conditions of high temperatures and densities are one of the most important trends of investigations in relativistic nuclear physics. The strategical aim of these investigations is the possibility to observe the phase transition : nuclear matter - quark - gluon plasma, predicted by theory. In particular it is predicted that this phase transition can happen in nucleus - nucleus collisions at temperatures of 0.15 GeV and energy densities of several GeV$/fm^3$ densities or the density of baryons several units larger than their density in a normal state.

The observation of the extreme conditions is made by detecting all kind of specific signals characterizing the given states of nuclear matter. To answer exactly the question on the first source of these signals, it is necessary to study in detail the properties of the main observed characteristics, describing the state of nuclear matter at different time intervals of nuclear collisions, over a wide range of collision energy and with a large set of colliding nuclei. The number of nucleons of the colliding nuclei is one of such characteristics. In this case the number of these nucleons can serve as a quantitative boundary separating these states from the ordinary ones.

The experimental data presented in our papers [1,2] have shown that the behaviour of the observed parameters, characterizing the interactions of relativistic nuclei with the carbon nucleus versus the number of secondary protons (Q) , is different for the events with $Q \geq Q^*$ and $Q \leq Q^*$. (where $Q = N^+ - N_{\pi^-}, N^+-$ $, N_{\pi^-}$ are the numbers of positive particles and π^- - mesons, emitted in the event, respectively). Here Q^* are some boundary values of Q. They turned out to be close to the values obtained from the condition

$$Q \geq 2Z/3 \tag{1}$$

This condition was used in [3] as a selection criterion for events with the total disintegration of the carbon nucleus (TDN) in interactions with π^- - mesons. Therefore, the authors of papers [1,2] suggested to use the condition

$$Q \geq Q^* \tag{2}$$

as a election criterion for events with TDN in interactions with relativistic nuclei. We also found that in the events with TDN there is a energy large dissipation for secondary particle production. It is possible that increasing the mean kinetic energy of nuclear matter is due to this dissipation. It is also not neglected that part of this energy can be used to increase the internal energy of nuclear matter - the production of high energy states.

If the notion of system "temperature" is introduced,the mean kinetic energy $< T >$ can be presented as the sum of energies which corresponds to the " temperature " of a system of these particles (T_0) and to the motion energy of this system itself (dT). The precise value of T_0 can be determined only within specific theoretical models. The experimental determination of $< T >$ can be carried out only under some assumptions following from the theoretical models. We are not going to use any models for a precise determination of T_0. We will be engaged in the search for a qualitative answer to the question on the possibility to increase this quantity due to the above dissipation of the energy of nuclear matter.

2 Methods of the experiment

The experimental data have been obtained from the 2-m propane bubble chamber of LHE, JINR. 8791 $\pi^- C$ - interactions at $P_{\pi^-} = 40 GeV/c$ (for the methodical details see [4]), and also 5284 - pC- ,6735 - dC-, 4852 - HeC- and 7327 - CC -interactions at a momentum of 4.2 A GeV/c(for methodical details see [5]) were used in this experiment.

The available statistical material was separated into the following groups by Q:

$$Q \geq 1; 2; 3; ...Q^*; ... \tag{3}$$

For each group of events, the spectra of the invariant inclusive cross sections $f = (E/\sigma)d^3\sigma/dp^3$ of secondary particles were obtained depending on the kinetic energy $T = E - m$ (here E and m are the total energy in the laboratory system and the rest mass of particles, respectively). Then these spectra were approximated by the expressions of the form

$$f(T) = a_{11} exp(a_{12} T), \tag{4}$$

$$f(T) = a_{21} exp(a_{22} T) + a_{23} exp(a_{24} T), \tag{5}$$

$$f(T) = a_{31} exp(a_{32} T) + a_{33} exp(a_{34} T) + a_{35} exp(a_{36} T), \tag{6}$$

and the best approximations were selected. The parameters $a_{12} = 1/ < T >_{12}, a_{22} = 1/ < T >_{22}, a_{24} = 1/ < T >_{24}$, $a_{32} = 1/ < T >_{32}, a_{34} = 1/ < T >_{34}, a_{36} = 1/ < T >_{36}$, and the quantities $< T >_{12}, < T >_{22}, < T >_{24}, < T >_{32}, < T >_{34}$ $< T >_{36}$ are assumed to characterize the mean value of T for different systems. The behaviour of the paremeters from (4-6) vs. Q were studied for the π^- - mesons and protons emitted in the interactions of π^- - mesons, protons and nuclei with carbon.

Such performance of the experiment allows us to study the Q-dependence of $< T >$ for different projectiles and to separate possible events showing the extreme states of nuclear matter, to determine the values of Q^* from the dependence $a_{ik} = g(Q)$ and to specify the selection criterion for events with TDN of the target .

For methodical complexities connected with the identification of π^+ - mesons, information about their spectra is not presented.

A similar analysis of π^- - mesons and protons was carried out in the groups of events characterized by the number of identified protons $N_p (N_p \geq 1; 2; 3; ...)$. As well as in [1,2], the results repeat those obtained for the groups of events from (3). Therefore, data on the N_p-dependence are not presented.

3 Experimental results

The $f = f(T)$ distributions are shown in figs. 1 - 6. The solid lines demonstrate the results of the best approximations. The best approximations of the $f = f(T)$ distributions at different Q turn out to be reached by functions (4-6) with a different number of components. Table 1 presents the number of components (the values of $\chi^2/(deg.fr.)$ are given in brackets) The parameters for the approximated functions $f(T)$ are respectively shown in fig. 7 (for π^-C-interactions) and 8-11 (for $pC-, dC-; HeC-; CC-$ -interactions).

In connection with this, we note that a question on the interpretation of the origin of the remaining components in the function $g(Q)$ arises in the case changing the number of summands. In principle there are two variants:

a) the remaining component is the continuation of none of the previous ones (i.e., at small values of Q);

b) the remaining component is one of the previous components.

In this case, it is necessary to make valid assumption of belonging the remaining component to one of the previous components. We have used the hypothesis about the smoothness of the function $g(Q)$.

The values of Q^* ,at which the regimes change in the invariant inclusive cross sections of protons and π^- - mesons are shown by arrows in figs. 7-11. The values of Q^* obtained in this paper and data from [2] are presented in Table 1. One can see that the obtained values of Q^* in these papers overlep each other. However, the data of the present paper are more precise.

Figure 7 shows the Q-dependence of the parameters a_{24} and a_{36} for π^-C - interactions. On basis the foregoing we assume that both of these parameters belong to the same high-impulse component of π^- - mesons. The revealed constancy of the above out parameters over in the range $Q \geq 1-5$ indicates the absence of perceptible energy losses of this component of π^--mesons.

Such a behaviour is characteristic of the quark- spectators hadronizing into the so - called "leading" pions [6]. Decreasing the corresponding preexponential multipliers speaks about sharp leaving the indicated pions from the leading class . A severe increase of the parameter a_{24} over the range $Q \geq 5 - 6$ demonstrates a "softer" channel of knocking out the "leading" π^- - mesons by transferring their energy to the low-pulse component. The decrease of the parameters a_{22}, a_{32} in the same range Q (see Fig. 7) is the argument in favour of this phenomenon. It is non excluded that the nonregularity in the behaviour of the parameter a_{34} (Fig.7) and also in the behaviour of a_{21} (at $Q \geq 3$) and a_{23} (at $Q \geq 3$) can be connected with the production of meson resonances (see Fig. 7).

The constancy of the parameter a_{24} for protons from pC, dC, HeC, CC interactions in the initial region of the argument Q is naturally explained (by analogy with the constancy of the parameters a_{24} and a_{36} the π^- - mesons in π^-C interactions) by the presence of the "leading" protons which emerge due to hadronizing diquarks - spectators. The systematic decrease of the parameter a_{24} or the increase of the corresponding mean kinetic energy of protons in nucleus-nucleus interactions with increasing the atomic weight of the projectile at $Q \geq 1$ (see Table 3) attract our attention.

The value of mean kinetic energy of protons $< T_p >$ in all the considered interactions decreases with increasing Q. In this case we have a large transfer of energy to an ever-growing number of nucleons of the nuclear target in the region of large values of Q beginning with Q^* and as a consequence, a sharp decrease of $< T_p >$.

The Q-dependence of the mean kinetic energy of π^- - mesons ($< T_{\pi^-} >$) turned out to be different for hadron - nucleus and nucleus - nucleus collisions. The experiment shows that the quantity $< T_{\pi^-} >$ decreases with increasing Q in π^-C and pC interactions.

The values of $< T_{\pi^-} >$ decrease in dC,^4HeC and ^{12}CC interactions at small values of Q. The low-energy component a_{22} demonstrates a sharp increase of $< T_{\pi^-} >$ with growing Q in ^4HeC ^{12}CC interactions at $Q^* \geq 6$. In this case there are the following differences for the He and C projectiles. Such values of $< T_{\pi^-} >$, as we have in events with $Q \geq 1$, are not reached for ^4He, even at the largest value of the Q. In the case ^{12}C at $Q \geq 6$ the values of $< T_{\pi^-} >_{22}$ are equal to or greater than those at $Q \geq 1$. Besides, in contrast to a monotonous increase of $< T_{\pi^-} >_{22}$ in the case of ^4He, a graded increase of its values is observed for ^{12}C. At $Q \geq 6$, the high-energy component (a_{24}) demonstrates either the constancy of $< T_{\pi^-} >_{22}$ for ^4HeC interactions or the increase of $< T_{\pi^-} >_{22}$ with increasing Q. In dC interactions the behaviour of the low-energy component differs from its behaviour in ^4HeC and ^{12}CC interactions. So, for example, the smallest value of $< T >$ is 80 MeV in ^4HeC and ^{12}CC interactions and 45 MeV for dC. A sharp increase of T_0 occurs at $Q \geq 3$.

Thus, from the afore-said it follows that:

1. In all the studied interactions, the value of $< T >$ decreases for all the groups of the observed protons with increasing Q. According to the data of paper [2], the mean multiplicities of protons increase. This fact can be explained by the dissipation of the energy of projectile nucleons between the increasing number of projectile nucleons from the nuclear target.

2. In π^-C and pC interactions at all the values of Q and in dC, ^4HeC and ^{12}CC interactions at $Q \leq Q^*$, the value of $< T >$ for π^- - mesons decreases with increasing Q. According to the data of the paper [2], the mean multiplicities of π^- - mesons increase under these conditions. This fact can be explained by increasing the number of interacting protons with growing Q.

3. The values of $< T >$ for π^- - mesons increase in dC, ^4HeC and ^{12}CC interactions at $Q \geq Q^*$. According to the data of paper [2], the mean multiplicities of π^- - mesons remain constant under these conditions, i.e. the increase of values Q in this region does not lead to increasing the mean multiplicities of π^- - mesons. Thus, the break of simple connexion between the number of collisions and Q is observed.

4 Conclusion

In conclusion, we have formulated the main results of the present paper:

1.The boundary values of Q^* (the number of protons in an event whose excess leads to qualitative changes in the behaviour of the invariant inclusive spectra of

proton and π^- - meson production) are obtained in π^-C ($P_{\pi^-} = 40GeV/c$) and pC, dC, ^4HeC, ^{12}CC (4.2 A GeV/c) collisions with carbon nuclei.

2.The events with $Q \geq Q^*$ correspond to the reactions with TDN.

3. A sharp increase of the mean kinetic energy of π^- - mesons and a sharp decrease of the mean kinetic energy of protons are observed in the region $Q \geq Q^*$ for nucleus - nucleus interactions with increasing Q.

4.The suppression of the "leading" effect is observed in the events with $Q \geq Q^*$.

Thus, we obtain that a large dissipation of the energy of colliding nucleons occurs in nucleus - nucleus interactions over the range $Q \geq Q^*$. This energy is spent on increasing the kinetic energy of π^- - mesons at their constant number, that is the bond between the number of collisions and the values of Q is broken. A contradiction arises: on the one hand a sharp increase of the number of protons and on the other hand, the constancy of the number of collisions. This contradiction can be overcome assuming that in the region $Q \geq Q^*$: - either there is a large contribution to Q of protons which are not involved in interactions. However, the suppression of the "leading" effect in this region with increasing Q and a strong dependence of the parameters of protons make this assumption invalid; - or the collective interactions of intranuclear nucleons take place. Here, one can proceed from the following physical picture. When the projectile nucleus interact with the target nucleus at a sufficiently large number of participants - nucleons of interaction, metastable state of nuclear matter can arised. It widens fast transferring its energy to a large number of nucleons of the colliding nuclei. Increasing the number of protons, decreasing their mean kinetic energy and the suppression of the "leading" effect are due to this phenomenon. In this case (at larger values of Q) the remainders of colliding nuclei turn out to be minimum. Therefore, π^- - mesons are emitted from this state with a minimum loss of energy. The smaller this remainder (or the larger Q), the larger the kinetic energy of emitted π^- - mesons. One can expect that at large masses (and, correspondingly, at low motion energies) the rest system of this formation can coincide with the laboratory system of coordinates. Then, the obtained values of $< T_{\pi^-} >$ can characterize the mean "temperature" of this extreme state of nuclear matter.

To verify these assumptions, it is necessary to study correllation phenomena within this experiment.

TABLE 1

Q	π^-C		pC		dC		HeC		CC	
	π^-	p	π^-	p	π^-	p	π^-	p	π^-	p
1	3(2.64)	2(1.70)	2(0.70)	2(1.55)	2(0.38)	2(2.52)	2(1.17)	2(2.64)	2(0.61)	2(2.29)
2	3(2.69)	2(1.75)	2(0.88)	2(1.33)	2(0.32)	2(2.93)	2(0.60)	2(2.45)	2(0.56)	2(2.18)
3	2(2.45)	2(1.66)	2(0.38)	2(0.55)	2(1.02)	2(1.58)	2(1.33)	2(2.10)	2(0.64)	2(1.94)
4	3(0.91)	1(1.03)	2(0.40)	2(0.70)	2(0.70)	2(1.15)	2(0.90)	2(2.33)	2(0.64)	2(1.70)
5	3(0.80)	1(0.87)	1(0.33)	2(0.70)	2(0.63)	2(1.25)	2(0.73)	2(2.01)	2(0.73)	2(1.44)
6	2(1.57)	2(0.73)	1(0.57)	2(0.65)	1(0.78)	2(0.85)	2(0.47)	2(0.93)	2(0.58)	2(1.22)
7	-	-	1(0.39)	2(0.39)	1(0.93)	2(1.23)	2(0.81)	2(1.02)	2(0.54)	2(0.92)
8	-	-	-	-	-	-	2(0.81)	2(1.46)	2(0.55)	2(1.72)
9	-	-	-	-	-	-	-	-	2(0.39)	2(1.35)
10	-	-	-	-	-	-	-	-	2(0.61)	2(1.65)
11	-	-	-	-	-	-	-	-	2(0.56)	2(1.54)
12	-	-	-	-	-	-	-	-	2(0.57)	2(1.25)

TABLE 2

The type of interaction	π^-C	pC	dC	HeC	CC
[2]	3-4	5-6	6-7	5-6	9-10
			8-9	12-13	
The present	3-4	5	4-6	4-6	6
paper					9-10

TABLE 3. The values of the quantity $< T >= 1/a_{24}$ at $Q \geq 1$.

The type of interaction	π^-C^*	pC	dC	HeC	CC
$< T >$	5.714	0.645	0.909	1.104	1.506
$< T > AC / < T > pC$	-	1	1.409	1.712	2.335

*) The values of parameters a_{36} of the π^- - mesons in π^-C - interactions were brought for the comparison.

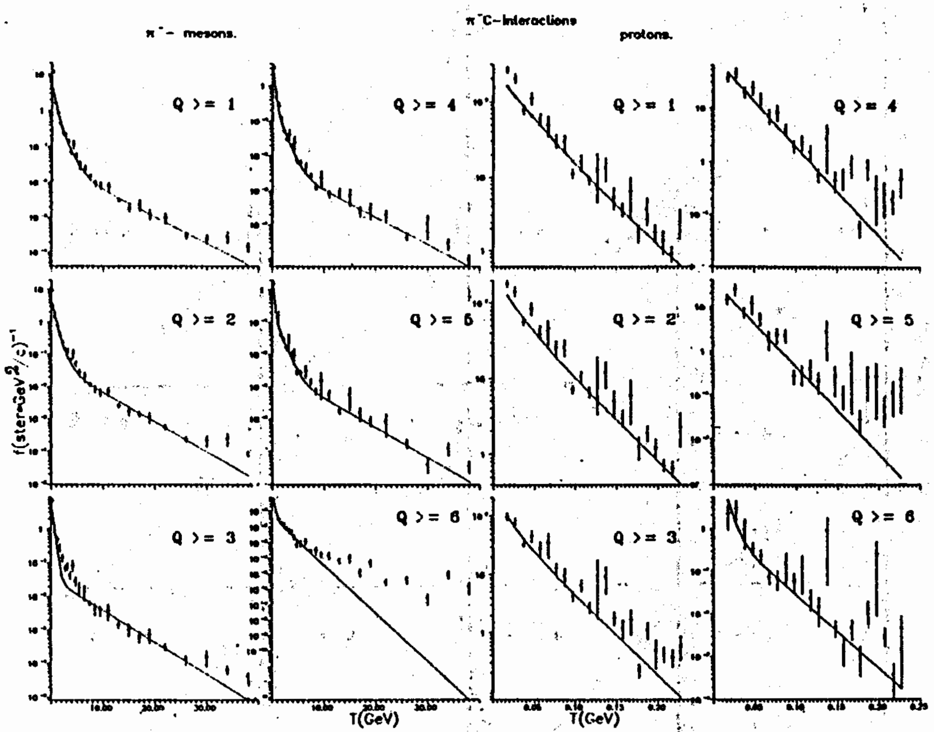


Fig.1.

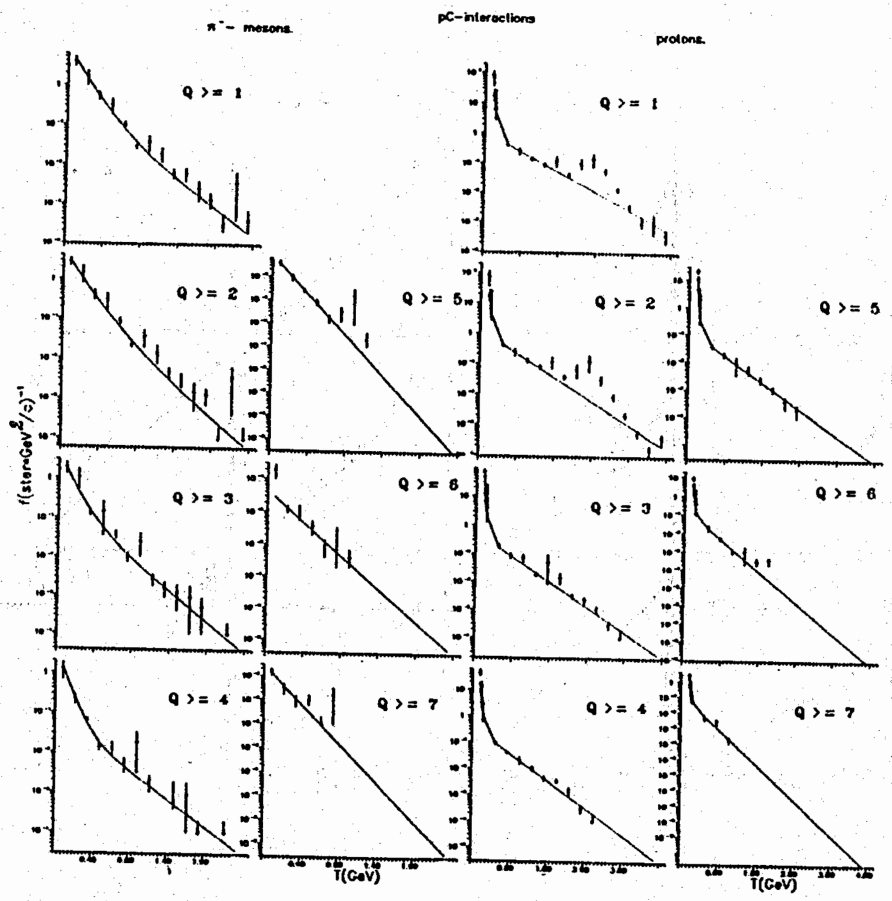

π⁻- mesons.
pC-interactions
protons.
Q >= 1
Q >= 2
Q >= 3
Q >= 4
Q >= 5
Q >= 6
Q >= 7
f(stereGeV²/c)⁻¹
T(GeV)

Fig.2.

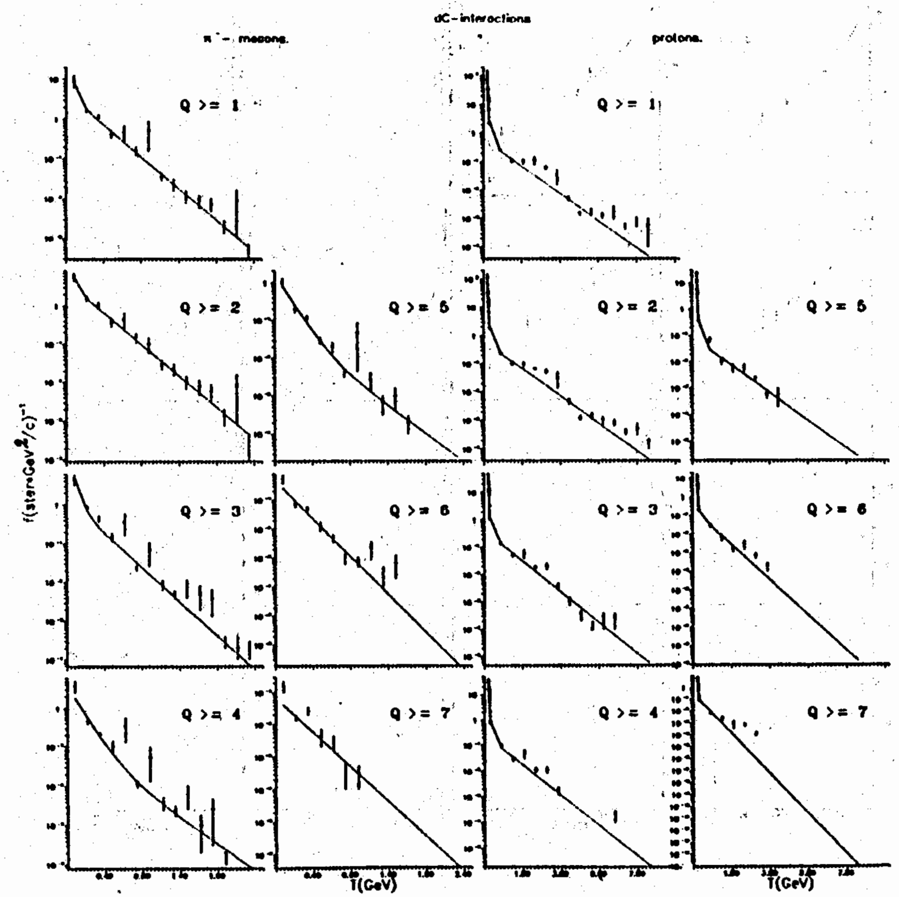

π⁻- mesons.
dC-interactions
protons.
Q >= 1
Q >= 2
Q >= 3
Q >= 4
Q >= 5
Q >= 6
Q >= 7
f(stereGeV²/c)⁻¹
T(GeV)

Fig.3.

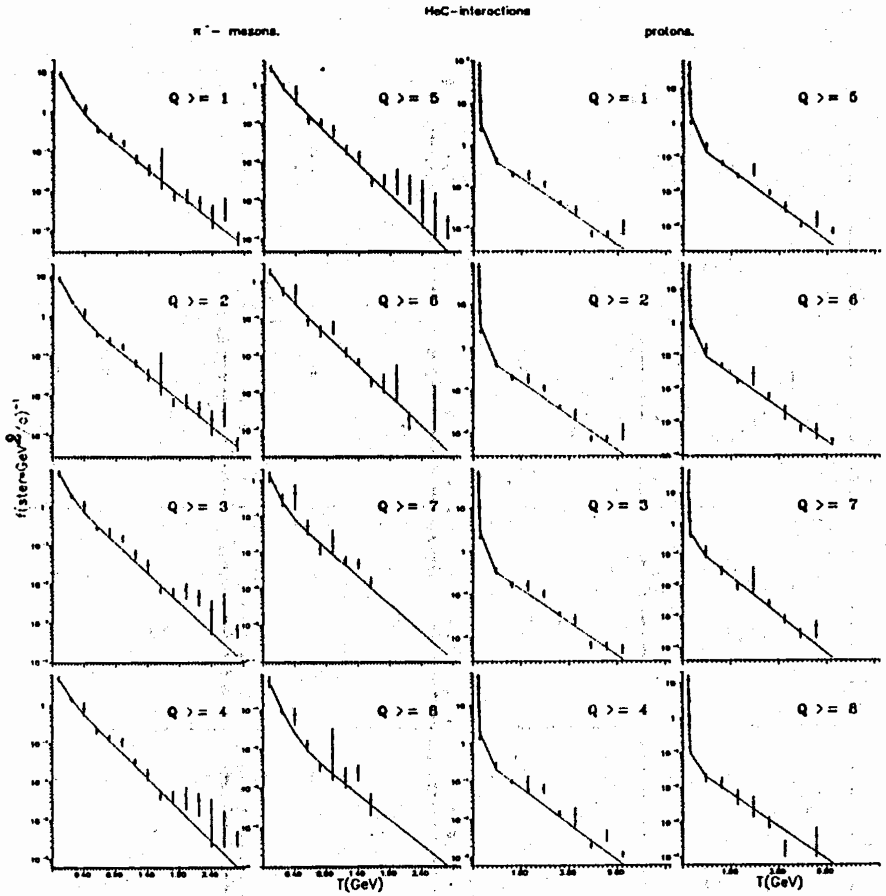

HeC-interactions
π⁻- mesons.
protons.
Q >= 1
Q >= 5
Q >= 1
Q >= 5
Q >= 2
Q >= 6
Q >= 2
Q >= 6
Q >= 3
Q >= 7
Q >= 3
Q >= 7
Q >= 4
Q >= 8
Q >= 4
Q >= 8
f(ster*GeV²/c)⁻¹
T(GeV)
T(GeV)

Fig.4.

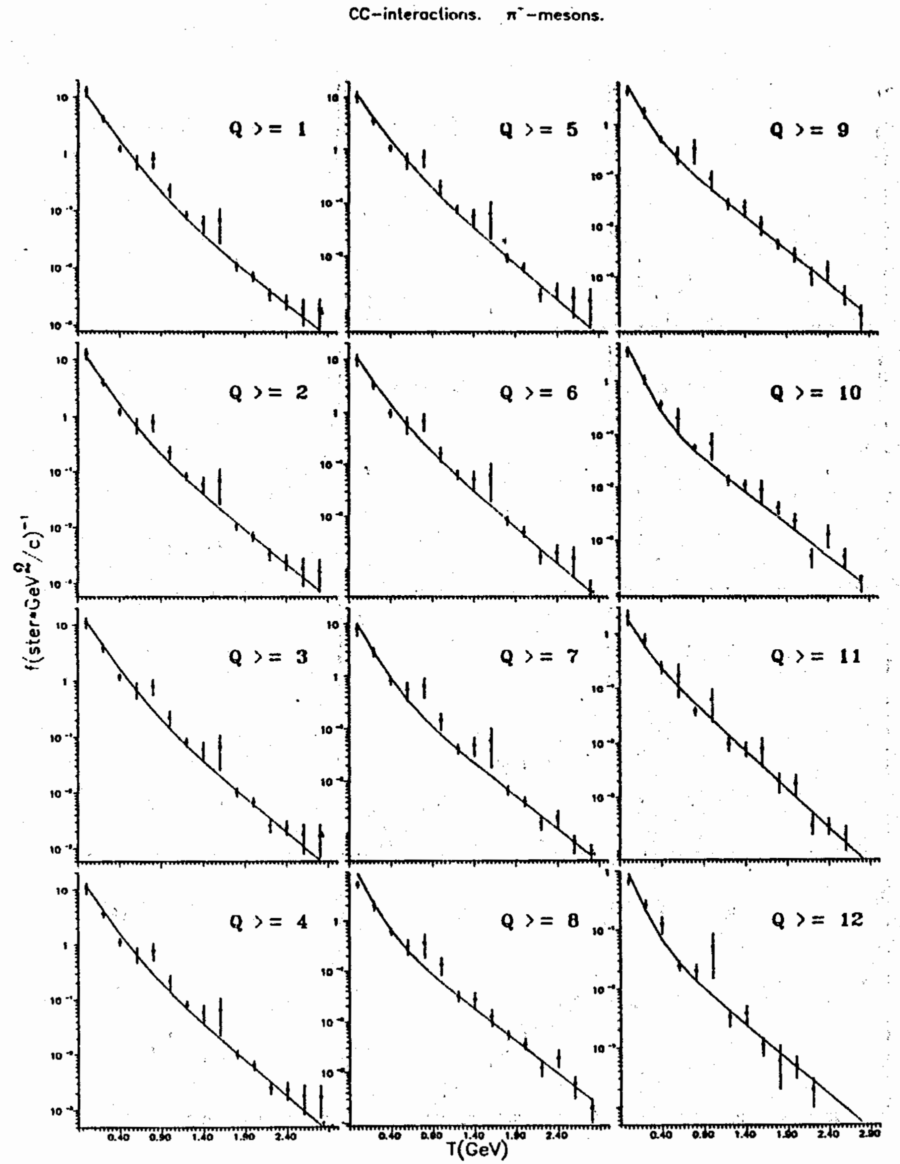

CC-interactions. π⁻-mesons.
Q >= 1
Q >= 5
Q >= 9
Q >= 2
Q >= 6
Q >= 10
Q >= 3
Q >= 7
Q >= 11
Q >= 4
Q >= 8
Q >= 12
f(ster*GeV²/c)⁻¹
T(GeV)

Fig.5.

CC–interactions. protons

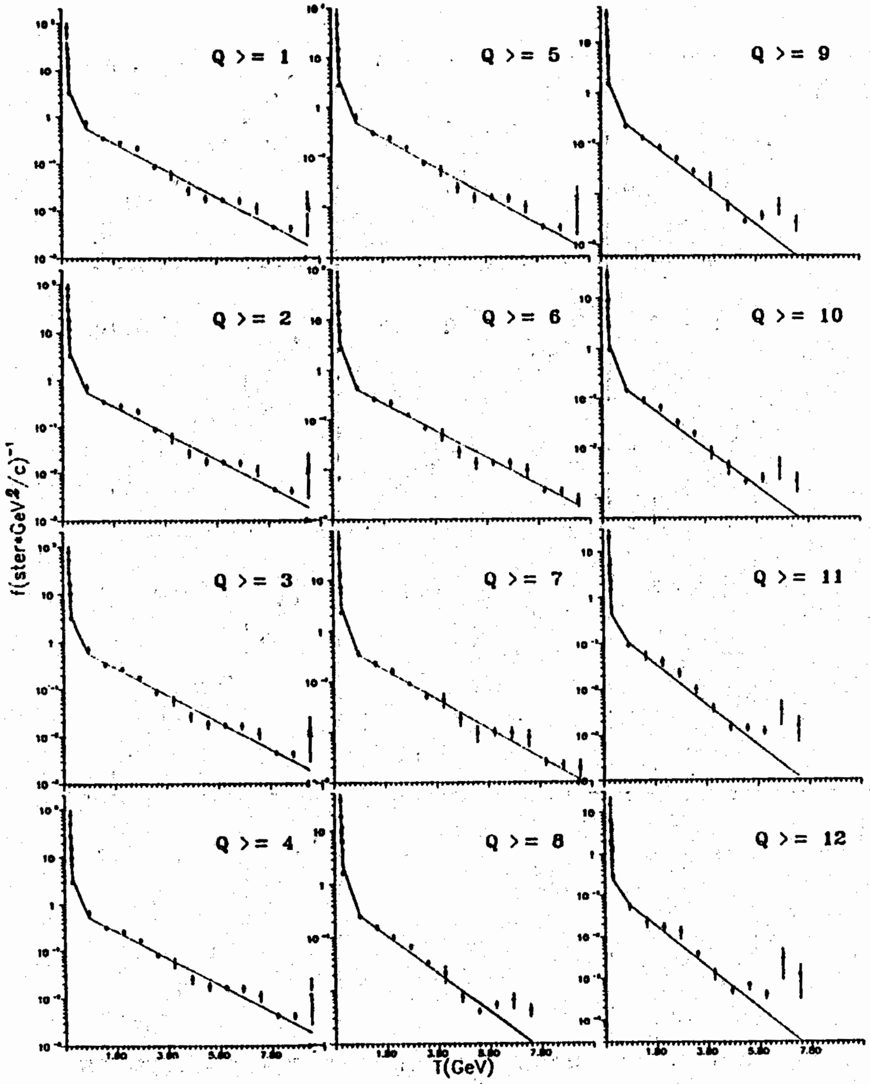


Fig.6.

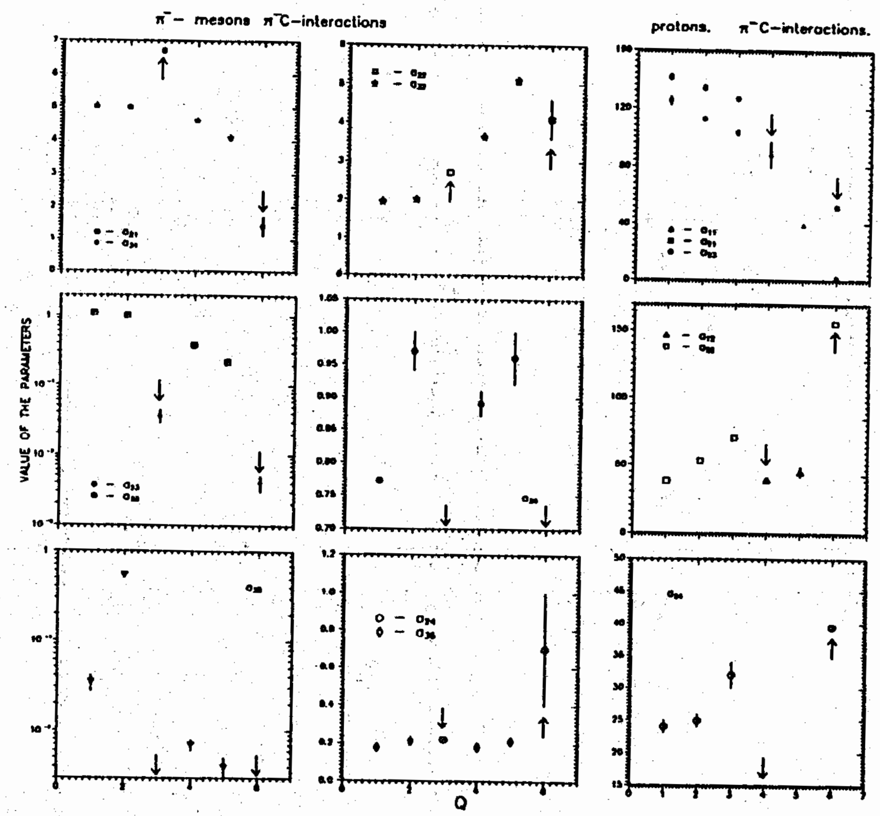
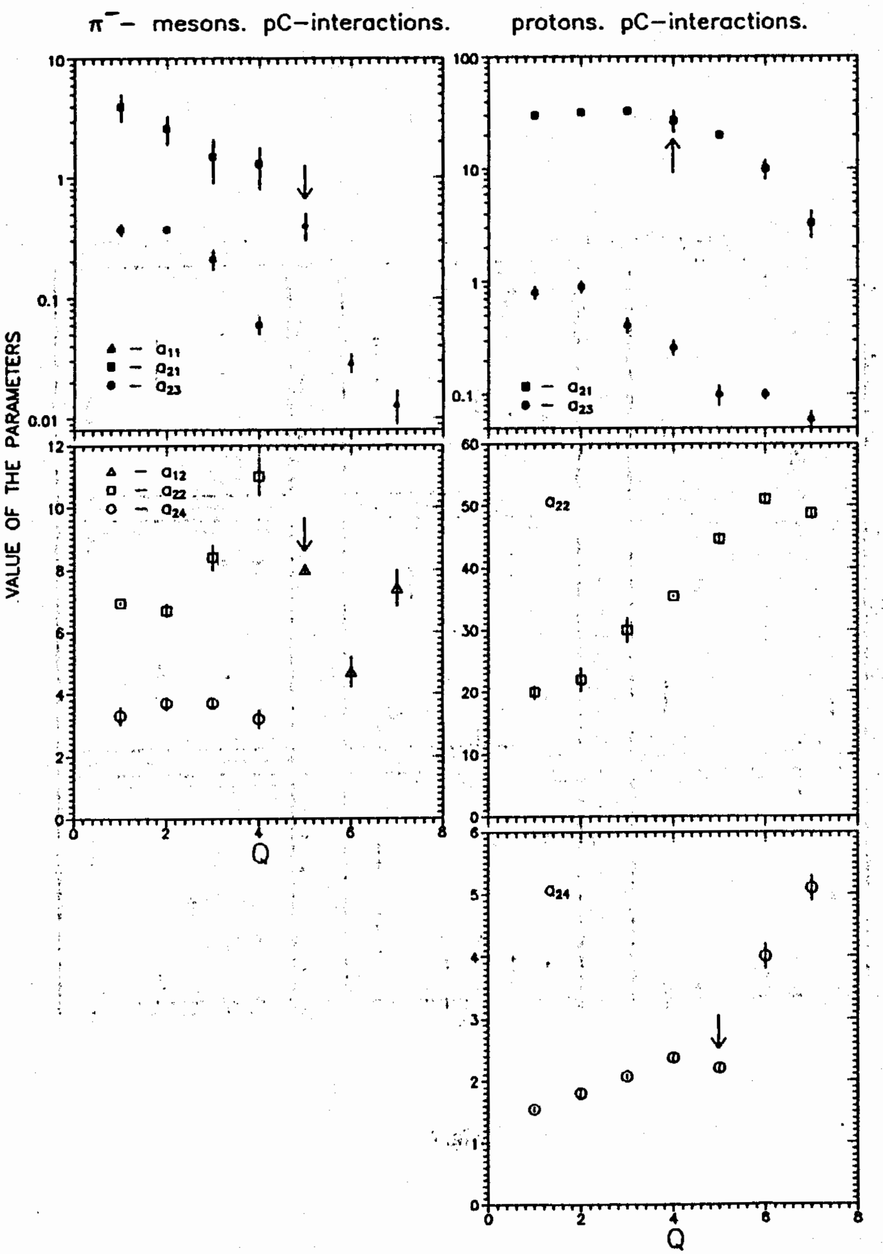
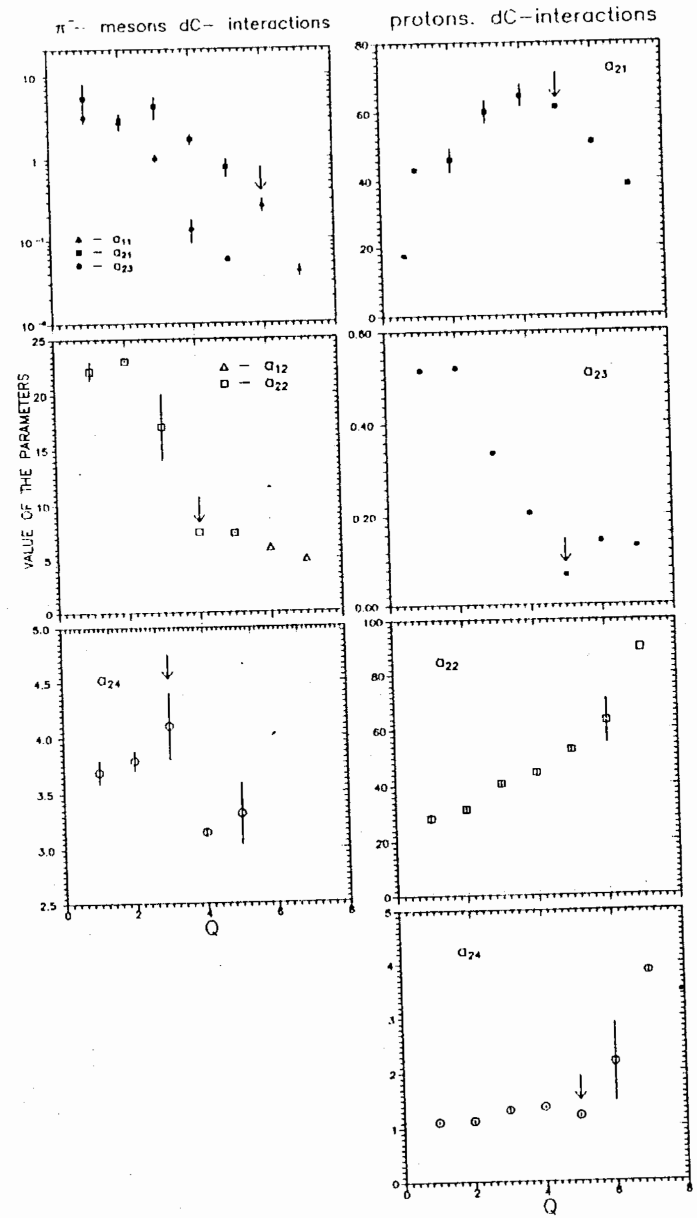


Fig.7.



π⁻– mesons. pC–interactions.
protons. pC–interactions.
VALUE OF THE PARAMETERS
▲ – a11
■ – a21
● – a23
△ – a12
□ – a22
○ – a24
■ – a21
● – a23
a22
a24
Q
Q

Fig.8.



π⁻– mesons dC– interactions
protons. dC–interactions
VALUE OF THE PARAMETERS
▲ – a11
■ – a21
● – a23
△ – a12
□ – a22
a24
a21
a23
a22
a24
Q
Q

Fig.9.

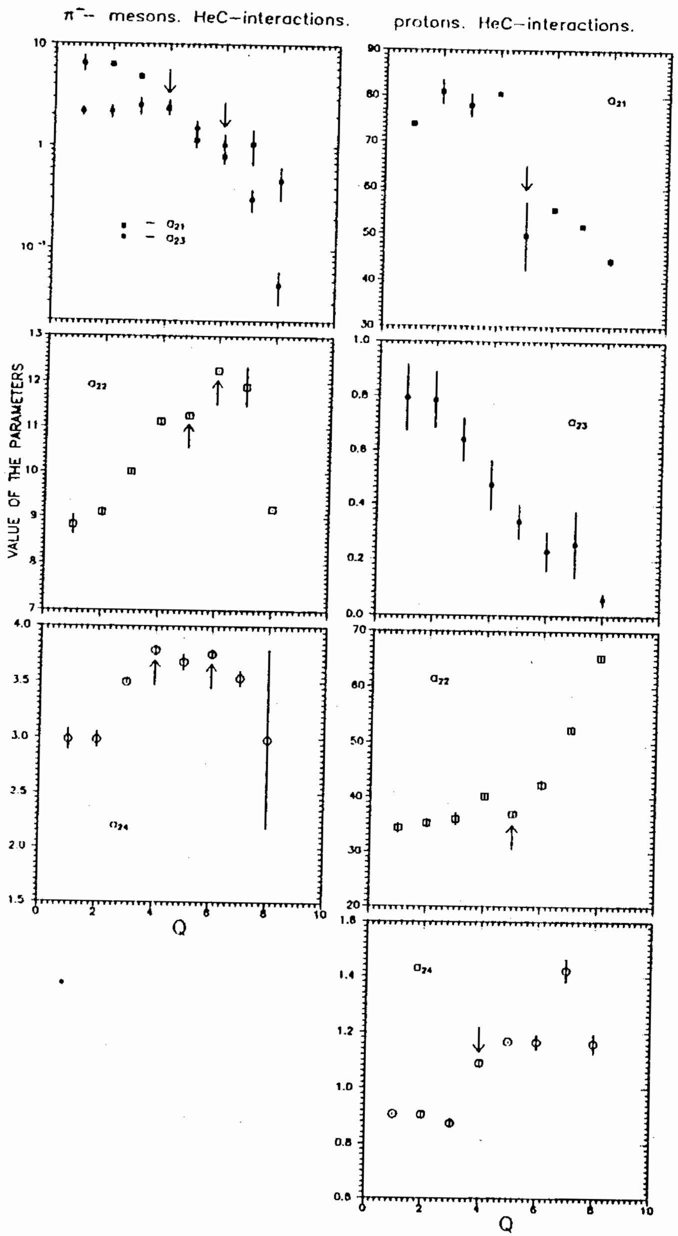

π⁻- mesons. HeC-interactions.
protons. HeC-interactions.
VALUE OF THE PARAMETERS
Q
a21
a22
a23
a24

Fig.10.

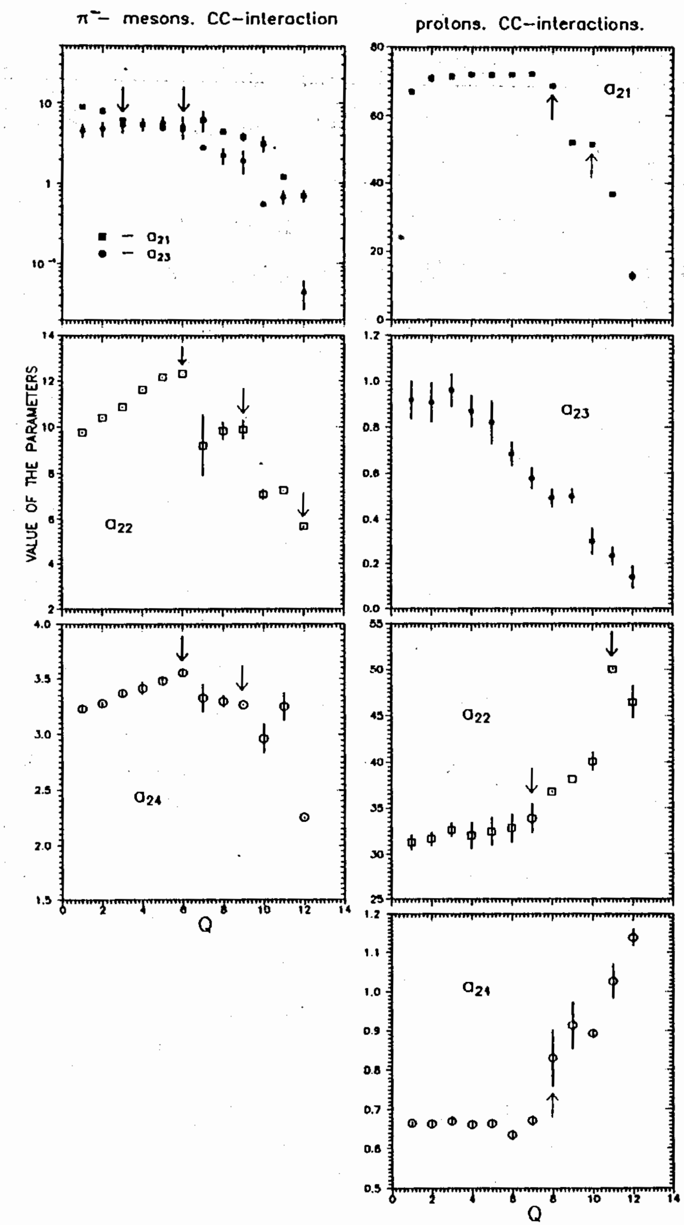

π⁻- mesons. CC-interaction
protons. CC-interactions.
VALUE OF THE PARAMETERS
Q
a21
a22
a23
a24

Fig.11.

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Received by Publishing Department
on June 4, 1997.

Абдинов О.Б. и др. E1-97-178

О возможности экспериментального исследования экстремальных состояний ядерного вещества. Инвариантные инклюзивные спектры вторичных частиц, образованных в π^-, p, d, ^{4}He, ^{12}C + C взаимодействиях

В работе использованы экспериментальные данные по π^-C-взаимодействиям при $P_{\pi^-} = 40$ ГэВ/с, а также pC-, dC-, ^{4}HeC- и ^{12}CC-взаимодействий при 4,2 A ГэВ/с. Экспериментальный материал был разделен на группы событий с числом протонов Q ($Q \geq 1;2;3;...$). Для каждой группы событий строились инвариантные инклюзивные спектры $f = (E/\sigma)\, d^3\sigma/dp^3$ для π^--мезонов и протонов в зависимости от их кинетической энергии — T в лабораторной системе координат. Эти спектры имели экспоненциальный вид и были аппроксимированы выражениями, состоящими из одной экспоненты, а также из суммы двух и трех экспонент. Отбирались лучшие аппроксимации и изучалось поведение параметров этих аппроксимаций в зависимости от Q. В результате подтверждено существование граничных значений $Q = Q^*$, при превышении которых происходят качественные изменения в свойствах рассматриваемых взаимодействий; показано, что события с $Q \geq Q^*$ соответствуют реакциям с полным развалом ядра мишени, в этой области в случае ядро-ядерных взаимодействий с ростом Q наблюдается резкое повышение средней кинетической энергии π^--мезонов и резкое понижение средней кинетической энергии протонов, в событиях с $Q \geq Q^*$ наблюдается подавление эффекта лидирования. Было выявлено нарушение связи между числом столкновений и числом протонов, т.е. увеличение количества протонов происходит при постоянном числе столкновений. Это противоречие объясняется тем, что в области $Q \geq Q^*$ имеет место возникновение и быстрое расширение некоторого метастабильного состояния — экстремальное состояние ядерного вещества.

Работа выполнена в Лаборатории высоких энергий ОИЯИ.

Сообщение Объединенного института ядерных исследований. Дубна, 1997

Abdinov O.B. et al. E1-97-178

On the Possibility of Experimental Investigation of Extreme States of Nuclear Matter. The Invariant Inclusive Spectra of Secondary Particles Production in π^-, p, d, ^{4}He, ^{12}C + C Interactions

The experimental data on π^-C-interactions at $P_{\pi^-} = 40$ GeV/c, also pC, dC, ^{4}HeC and ^{12}CC-interactions at a momentum of 4.2 A Gev/c are used in this paper. The statistical material was separated into the following groups with the number of protons Q: $Q \geq 1;2;3;...Q;$ .... The invariant inclusive spectra of π^--mesons and protons $f = (E/\sigma)\, d^3\sigma/dp^3$ versus their kinetic energy T in the laboratory system of coordinates were obtained for each group of events.

These spectra are of the exponential form, and they were approximated by the expressions consisting of one exponent, the sum of two exponents and the sum of three exponents. The best approximations were selected, and the behaviours of the parameters from these approximations were studied depending on Q. As a result, the boundary values of Q^*, under the excess of which qualitative changes in the properties of the considered interactions take place, are verified. It is shown that the events with $Q \geq Q^*$ correspond to the events with the total disintegration of the nuclear target. In this region a sharp increase of the kinetic energy of π^--mesons and a sharp decrease of the kinetic energy of protons are observed for nucleus-nucleus interactions with increasing Q. The suppression of the "leading" effect is observed in the events with $Q \geq Q^*$. We have discovered a connection between the number of collisions and the number of protons, i.e. increasing the number of protons at a constant number of collisions. This contradiction is explained by that there is fast widening of some metastable state, the extreme state of nuclear matter, in the region $Q \geq Q^*$.

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

Communication of the Joint Institute for Nuclear Research. Dubna, 1997