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DESCRIPTION OF INELASTIC NUCLEUS-NUCLEUS INTERACTIONS AT MEDIUM ENERGIES USING DUAL PARTON MODEL

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Introduction

Last years great experimental efforts have resulted in a large amount of information about inelastic nucleus-nucleus interactions. In particular, the main characteristics of the processes at low, medium and high energies were determined. For interpreting these data and determining the promising investigation directions it is necessary to develop the existing theoretical approaches and work out new ones. One of the important problem on this way is to elaborate a unified theoretical scheme in the whole interval of the accelerating energy.

It is clear that this scheme have to explicitly allow for the quark structure of hadrons for a description of hard and semihard QCD-processes at high energies and take into account the restricted phase space effects at medium energies. It is also obvious that it must treat both quark hadronisation processes and nonobservability of the color charges, i. e., to be based on any solution of the confinement problem. Since this problem has not been solved in QCD at present, one should use various phenomenological and semiphenomenological approaches. Let us consider the best known approaches from the point of view of these requirements.

As is known, to interprete experimental data on inelastic nucleus-nucleus interactions at low and medium energy, a cascade-evaporation model [1], based on the macroscopic treatment of purely quantum mechanical phenomena, in particular, on the representation of the total interaction as the incoherent set of elementary local hadron-nucleon interactions, is successfully used. The basic assumptions of this model are violated with increasing energy of colliding nuclei due to increase of characteristic longitudinal distances and coherence degree of the processes. Therefore extending the model to the high energy region requires introducing some more new assumptions, often without sufficient theoretical substantiation (see [2]). Besides, description of the processes at a hadronic level alone, as is inherent to the cascade models, requires the information about both known and unknown properties of particles. The last circumstance stimulated the elaboration of the models based on radically different suggestions.

At present the LUND-model [3] and the dual parton model (DPM) [4] (see for refs.[5]) are the most popular among them. The popularity of the LUND-model, however, is due to alluring simplicity of its basic principles rather than their fundamentality and to wide accessibility of its program implementation as well as to successful application of its string fragmentation scheme of hadronization for describing e^+e^- annihilation processes.

The dual parton model compares favourably with the LUND-model. First, it is based on ideas of $1/N_f$ expansion of QCD [6] and can be connected in principle with the QCD perturbation theory. Thus, one can describe the effects of the QCD growth of characterisic cross momenta at high energy. Secondly, problem of the confinement mechanism and the hadron structure is not so much acute in DPM, being "hidden" into the concept of "constituent quarks" and treatment of low mass string. The further development of the model toward the high energies is likely to follow the way of filling up the concept of "constituent quark" by the QCD content and toward the low energies the low mass strings behaviour will be specified. However, owing to the fact that the characteristics of the processes at non high energies are defined by phase space constraints rather than by fine structure of matrix elements, one can hope that taking into account only energy-momentum conservation law within the framework of DPM will permit to satisfactory describe experimental data at medium energies. This question is partially solved by our "putting-onto-mass-shell" algorithm [7] that can take account of DPM restrictions. It allows essential (to 2 - 3 GeV) decrease in the DPM applicability threshold.

It should be noted that DPM of hadron-nucleus and nucleus-nucleus processes is genetically connected with the Regge interpretation of the Glauber approximation and Abramovski-Gribov-Kancheli cutting rules (AGK) [8]. Correction of the latter for finite energy allows, as will be shown below, to describe satisfactorily the main characteristics of inelastic nucleus-nucleus interactions at medium energy. Thus, in the present paper a problem of extending the dual parton model to the medium energy region is solved. A more complicate problem of extendig the model to very high energy region is being solved. The plan of the paper is as follows. In section 1 we give the main assumptions of DPM and consider a correction procedure for the number of inelastic interactions. In section 2 an important distinctive feature of our program implementation of DPM - taking into account diffraction processes to the low mass states - is discussed. The simulation algorithm of nucleus-nucleus inelastic interactions is briefly described in section 3. The last section contains the simulation results and their discussion.

1. The Main Assumptions of DPM and the Correction Procedure for the Number of Inelastic Intranuclear Collisions

Briefly the main assumptions of DPM [4] are reduced to the following:

i) During the process of an inelastic hadron-nucleus (hA) collision an incident hadron is divided into a definite number of subsystems equal to the number of nuclear nucleons with which an interaction took place. Each subsystem represents a valence quark - valence diquark (valence antiquark in the case of incident meson) pair or a quark-antiquark pair. Nuclear nucleons, taking part in collision, are represented only in the valence quark-valence diquark state.

Distribution over the number of subsystems or the number of touched ("wounded") nucleons is given by the Glauber expression

$$P_\nu = C_A^\nu \frac{1}{\sigma_{hA}^{prod}} \int d^2b \left[\sigma T(\vec{b})\right]^\nu \left[1-\sigma T(\vec{b})\right]^{A-\nu}, \qquad (1)$$

$$\sigma_{hA}^{prod} = \int d^2b \left\{ 1 - \left[1 - \sigma T(\vec{b})\right]^A \right\},$$

$$T(\vec{b}) = \int_{-\infty}^{+\infty} \rho_A\left(\sqrt{b^2+z^2}\right) dz,$$

where A is the mass number of the target nucleus, σ is the inelastic hadron-nucleon cross section, ρ_A is the one particle nucleus density.

In the case of nucleus-nucleus (AA) collisions every "wounded" nucleon of both the projectile nucleus and the target nucleus is divided into the subsystems. For any given "wounded" nucleon, for example, of the projectile nucleus, the number of the subsystems is equal to the number of nucleon of the target nucleus with which it has interacted. The distribution over the subsystem numbers can also be obtained within the framework of the Glauber approach (see [11]).

ii) Between the subsystems of various hadrons QCD-strings are formed, producing new hadrons. In Fig.1, for example, possible string formation schemes in barion-barion interactions are given.

iii) The strings independently fragmentate similarly to the strings formed in e^+e^- annihilation processes at not very high energies.

According to the model, the string formation scheme in hadron-nucleus collisions is given in Fig.2. It is clear that it cannot be realized on a heavy nucleus at moderate energies. Indeed,

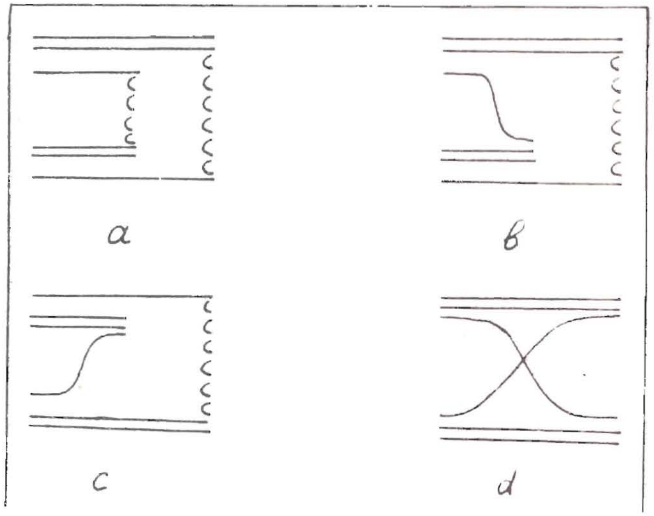

Fig.1. String formation scheme in barion-barion interactions.

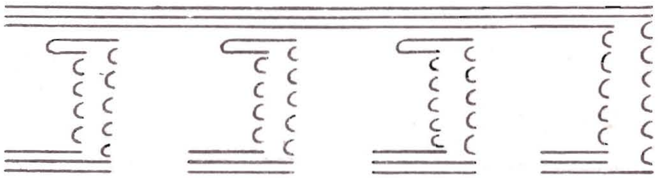

Fig.2. String formation scheme in hadron-nucleus interactions.

minimal energy of a string in the target nucleus rest frame is of the order of 1 GeV. Therefore, an interaction of the hadron, of energy E_0, with a hundred nuclear nucleons, possible according to the distribution (1) at a sufficiently heavy target nucleus , is impossible at $E_0 < 200$ GeV. These interactions beeng completely forbidden, the Glauber expressions would be distorted and, therefore, Regge interpretation of Glauber approximation would be violated. In this situation it is necessary to change string formation scheme by including the elements like those in Figs. 1b-1c. It corresponds to taking into account the dominance of the nonvacuum changes in the t-channel in elastic scattering at moderate energies. However, if we use the experimentally defined characteristics of nucleon-nucleon collisions in calculation of the Glauber expressions, we will effectively take into account such changes. Therefore, the number of intranuclear interactions can only be restricted at the stage of applying AGK cutting rules [8] to the elastic scattering amplitude. We suppose the most consistent way to realize that is to follow the spirit of the additive quark model[12], according to which at $A \to \infty$

$$P_\nu = C^{\nu}_{N_s} \frac{1}{C^{prod}_{hA}} \int d^2b \left\{1 - \exp\left[-\frac{C}{N_s} \cdot A \cdot T(\vec{b})\right]\right\}^{\nu} \cdot \tag{2}$$

$$\cdot \exp\left[-\frac{N_s - \nu}{N_s} \cdot C \cdot A \cdot T(\vec{b})\right].$$

Here $N_s \approx (E_0/2\ \mathrm{GeV})$ is the maximum number of hadron quark subsystems which can manifest themselves at a given energy E_0.

Note, that this correction allows the structure of the Glauber expressions to be retained, because the distribution (2) results from (1) if the first interaction of possible those ν dictated by (1) always takes place, the second one[1] occurs with the probability $(N_s-1)/N_s$, the third one occurs with the probability $(N_s-2)/N_s$ if the second one has occured, otherwise its probability is $(N_s-1)/N_s$, etc.[2], i.e., the probability of the i-th possible interaction is $(N_s-N_R)/N_s$, where N_R is the number of the interactions occured. In the case of nucleus-nucleus collisions the probability of the i-th nucleon of the projectile nucleus interacting with the j-th nucleon of the target nucleus should be defined as $(N_s-N_{Ri})(N_s-N_{Rj})/N_s^2$, where N_{Ri} and N_{Rj} are numbers similar to N_R for the i-th and j-th nucleons.

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[1] Various sequences of the interactions are assumed to be equally possible.

[2] This algorithm is a modification of the "maximum-cross-section" method[14].

Let us note the obvious consequence of the suggested correction procedure of the asymptotic AGK rules:

i) Due to suppressing the number of sea subsystems the behaviour of the energy dependence of the strange particle yield in hA and AA interactions in the medium energy region has to differ from the similar one in pp interaction;

ii) At a fixed interaction energy the inclusive cross-section of strange particle production must be proportional to A^1 on light nuclei and to $A^{2/3}$ on heavy ones.

iii) Because of dominating processes of Fig. 1d at low energy (due to Regge phenomenology) and owing to the correction of the number of interactions the inelastic nuclei collisions look like a set of independent nucleon-nucleon interactions.

The last conclusion is correct if diffraction dissociation processes are neglected, though they can be taken into account in DPM.

2. Description of the Diffraction Dissociation to the Low Mass State

According to the Born approximation of QCD, the diffraction dissociation (DD) processes to the low mass states are described by the diagram set of Fig. 3, where gluons are represented by wavy lines and quarks and antiquarks (diquarks) by straight ones. Using the technique of the papers [15] one can get the amplitude of the process and determine all characteristics of DD. However, the use of this approach for hadron-nucleus and nucleus-nucleus interactions is rather complicated. Therefore let us restrict ourselves by the diagram of Fig. 3d alone, interpreting it as a process of macroscopic scattering of the conserving hadron on quark

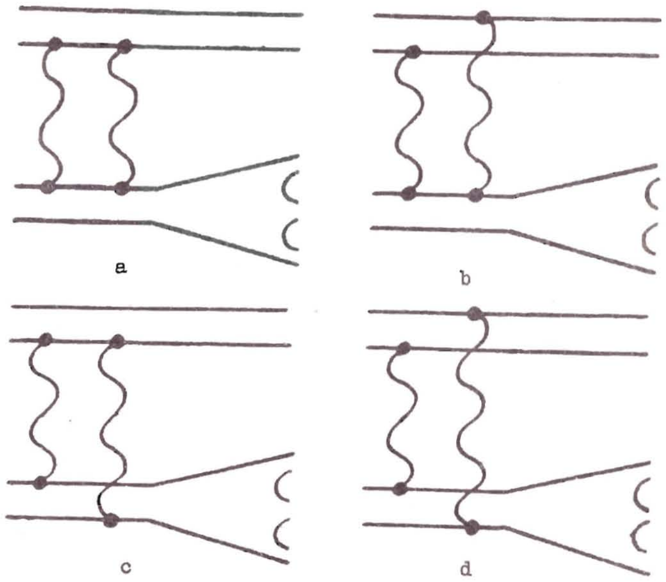

Fig.3. The process of diffraction dissociation to the low mass states within the QCD Born approximation.

constituents of the dissociating hadron. Using the "putting-onto-mass-shell" procedure [7] and assuming that the distribution over transverse transfer at every scattering act is given by the function $\exp(-Bq^2)$ ($B \approx 20\ (\mathrm{GeV}/c)^{-2}$)3) and the quark distribution over the fraction of the longitudinal momentum x is given by the expression

$$f(x) \sim \frac{1}{\sqrt{x}}\,(1-x)^{b}, \qquad (3)$$

where b = - 0.5 for mesons and 2 - 2.5 for barions, we have a possibility of exclusive description of DD processes4).

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3) It is determined on the basis of calculation in the Born approximation by using all graphs of fig.3.

4) Description of the DD processes to the high mass states was considered in [6].

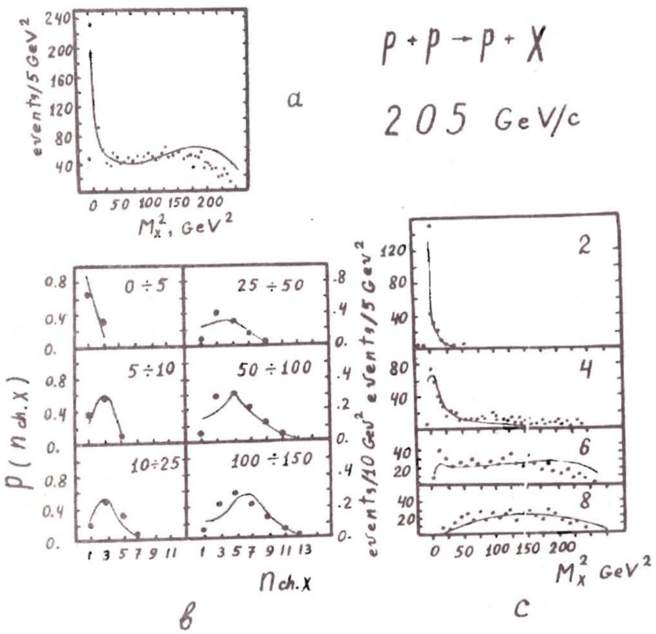

Fig.4. Characteristics of the reaction $p + p \rightarrow p + X$ at 205 GeV/c:

a) Distribution over the mass of the produced system X.

b) Distribution over the charged particle multiplicity in the system X at various values of M_X^2 (shown in the Figure).

c) Distribution over M_X^2 at various multiplicities of secondary charged particles in the reaction. The curves are our calculations, points are the experimental histograms from the paper [17,18].

In Fig. 4 the results of theoretical calculation (curves) together with the experimental data [17,18] are given. As is seen, the agreement is quite satisfactory.

Generalization of the algorithm suggested is quite obvious and is demonstrated in Fig. 5.

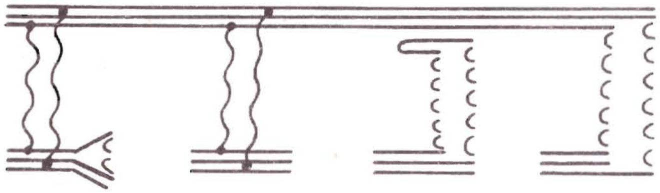

Fig.5. String formation scheme in hadron-nucleus interactions with allowance for the diffraction dissociation processes.

Note that the taking into account of DD processes allows a better description level of the data at high energies (see [19]).

3. Simulation Steps of Inelastic Nucleus-Nucleus Interactions at Medium Energies

The simulation of inelastic nucleus-nucleus interactions includes the following steps:

i) Determination of the interaction configuration of the nuclear nucleons according to the Glauber expressions using the method [13].

ii) Determination of the type of each elementary interaction (diffractional or nondiffractional) according to the existing cross section estimation.

iii) Correction of the number of nondiffractional interactions.

iv) Determination of the kinematic characteristic of quarks and antiquarks (diquarks) (Distribution of the valence quarks over the value of x was taken in the form (3). For sea quarks the distribution 1/x was used. The transverse momentum of the quarks was sampled from the exp(-Bq) distribution, $B \approx 6\ (\mathrm{GeV/c})^{-1}$). The sum of the transverse quark momenta was ascribed with the minus sign to the nucleon diquark. We deal with the fraction of the longitudinal momentum in a similar way. At given values of x_i and q_i the "putting- onto-mass-shell" [7] procedure was used provided the masses of quarks and diquarks are zero.

v) Determination of kinematic characteristics of the strings and their fragmentation. For the latter purpose we used a code BAMJET [20], modified by us.

vi) Simulation of the decays with the help of the code DECAY [21].

4. The Results of Simulation and Their Discussion

As is known, the experimental investigation of nucleus-nucleus interactions by using the standard bubble and streamer chamber methods are more complicated than the similar investigations of hadron-hadron and hadron-nucleus collisions, because of both the large reaction cross sections and the large multiplicity of produced particles collimated in the narrow angle interval already at comparatively small energies. This hampers identification and separation of the particles. Negatively charged particles are detected reliably enough. Therefore let us turn to a description of their characteristics.

Note that the values of cross section for reaction with production of negatively charged particles which are often presented in experimental papers, do not allow one to judge about the total cross section value, for there are processes with production of neutral particle and processes not accompanied by creation of new particles (elastic scattering, dissociation of one or both nuclei, etc.). Separation of elastic and quasielastic scattering entails definite experimental difficulties. Therefore a direct test of the Glauber theory of multiple scattering predictions, on which DPM is based, seems impossible when using bubble and streamer chambers. One can suppose that the main difference between the theory predictions and experimental data consists both in general normalization and in estimation of the fraction of events not accompanied by production of negatively charged particles. Figs. 6,7 present the calculated distributions over the multiplicity of negatively charged particles

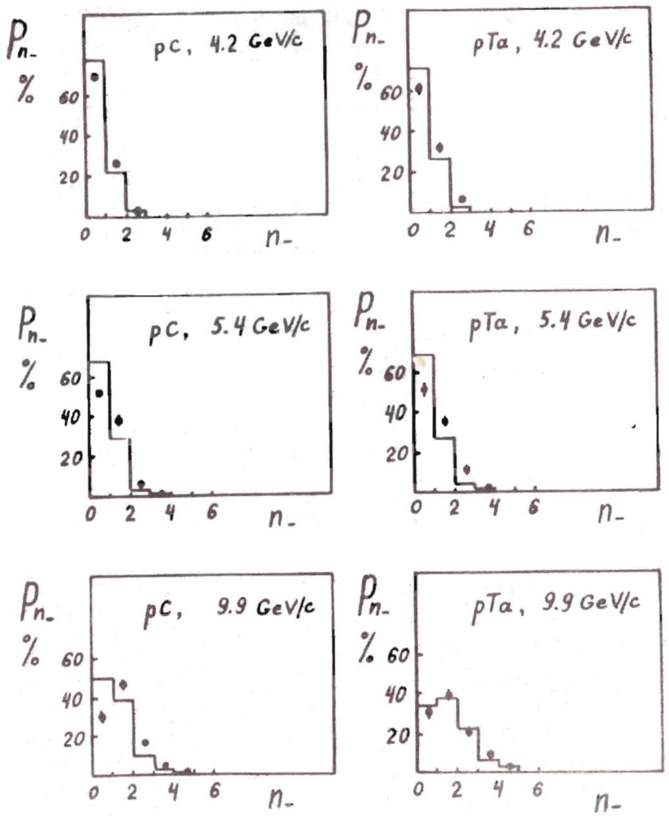

Fig.6. Distribution over the negatively charged particle multiplicity in hadron-nucleus interactions. The points are the data [22], histograms are our calculations.

in nucleus-nucleus interactions normalized to cross sections of inelastic collisions calculated using parameters determined at interpretation of high energy data [19].On the whole,as is seen from Figs. 6,7, agreement between the theory and the experiment is quite satisfactory. The most essential differences, as one should expect, are observed at low multiplicities.

Computing the Glauber cross sections of inelastic processes, we used the compilation data [24] on the characteristics of

nucleon-nucleon interactions such as the total cross-sections, the slope of the elastic scattering differential cross section and the ratio of real to imaginary part of the scattering amplitude at zero transfer. The cross section of single diffraction to the low mass states was considered as a fitting parameter and was chosen to be 0, 5 and 10 mb. The average multiplicity of the particles appeared to be less sensitive to this parameter. To reproduce the momentum characteristics of negatively charged particles we chose the value 5 mb.

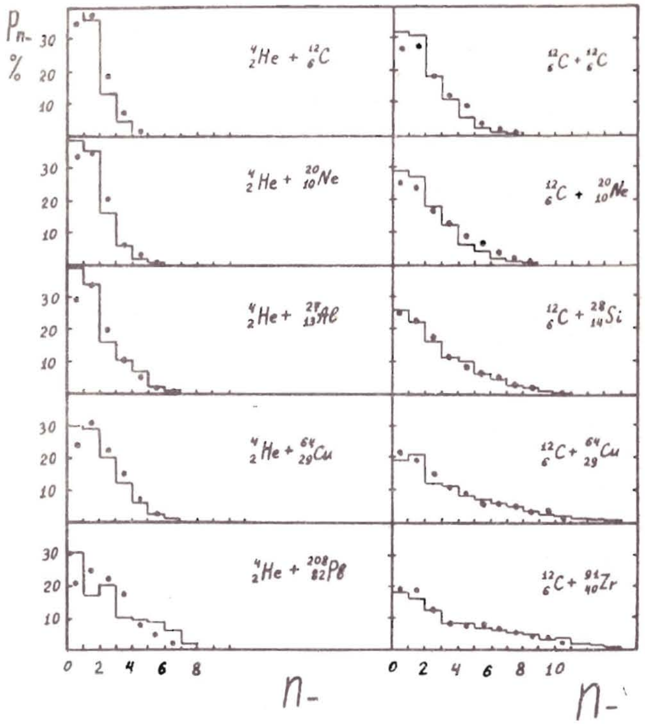

Fig.7. Distribution over the negatively charged particle multiplicity in nucleus-nucleus interactions at the incident nucleus momentum equal to 4.5 GeV/c per nucleon. The histograms are our calculations, the points are the experimental data [23].

Table 1.

The average multiplicity of π^--mesons in hadron-nucleus interactions (the experimental data are from the paper[22])

p_{inc} (GeV/c)		4.2	5.4	9.9
pC	exp	0.33±0.02	0.52±0.03	0.93±0.04
	th	0.22	0.36	0.67
pTa	exp	0.45±0.02	0.65±0.03	1.17±0.04
	th	0.32	0.45	1.05 .

Table 2.

The average multiplicity of π^--mesons in nucleus-nucleus interactions at the incident nucleus momentum equal to 4.2·A GeV/c (the experimental data are from the paper[25])

A_T \ A_P		d	α	C
C	exp	0.60±0.03	1.02±0.03	1.50±0.05
	th	0.44	0.63	1.00
Ta	exp	0.86±0.03	1.42±0.06	3.20±0.10
	th	0.81	1.50	3.0

Fermi motion of nuclear nucleons wasn't allowed for. We also neglected the cascading of the secondary particles and possible elastic rescatterings of nucleons up to inelastic interaction.

Tables 1,2 show the experimental and calculated data of the average multiplicity of π^--mesons, produced in nucleus-nucleus interactions. Noteworthy is the fact that agreement between the theory and the experiment is essentially better for heavy nuclei than for the light ones. To search for the reason for this discrepancy let us turn to the momentum characteristics. As seen from the Fig. 8, in the experimental events on heavy nuclei there is an admixture of π^--mesons with small momenta and large angles of flight, which is not described by the model. These π^--mesons are most likely to result from nucleon rescattering in the residual nucleus. Note that the presence of these rescatterings does not contradict the Regge interpretation of the Glauber approximation, in contrast to the rescattering of the produced particles. One can suppose the contribution of such rescatterings on light nuclei to be small. However, the experimental data and the calculated distributions presented in Fig 9 do not allow this statement to be checked because of systematic discrepancy in normalization.

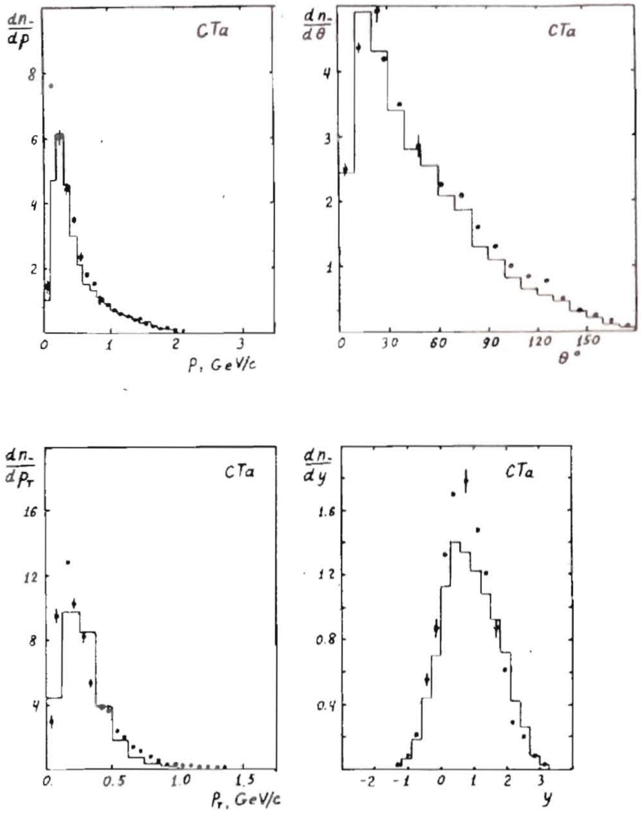

Fig.8, Various characteristics of π^--mesons produced in the interactions of ${}^{12}_{6}C$ + ${}^{181}_{73}Ta$ at the incident carbon nucleus momentum equal to 4.2 GeV/c per nucleon. The points are the experimental data [26], the histograms are our calculations

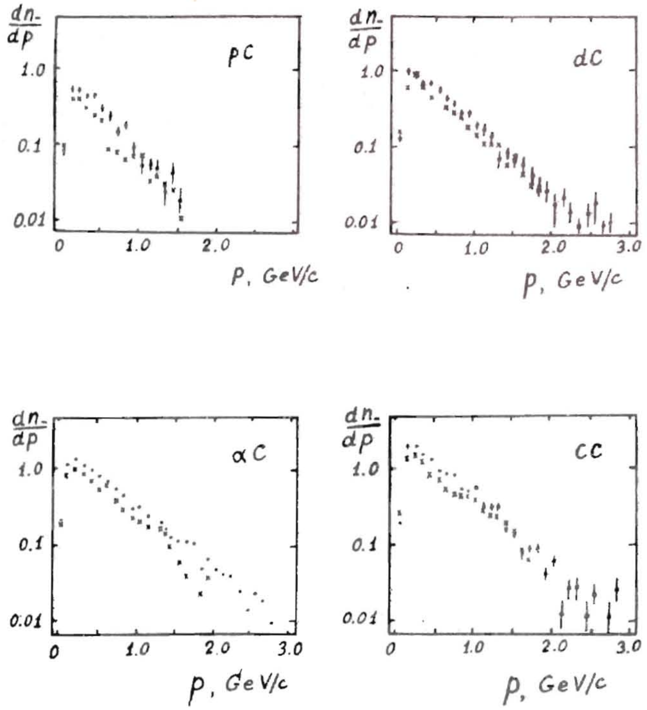

Fig.9. Momentum distributions of π^--mesons in nucleus-nucleus interactions at the incident nucleus momentum equal to 4.2 GeV/c per nucleon. • are the experimental data [26], × are our calculations.

Treating the events from the propane bubble chamber, the experimentators separate them into interactions with protons and with carbon nuclei. In doing so, quasifree interactions are often put into the first class of events, which may be the reason for the discrepancy between the theory and experiment in the characteristics discussed .

The general normalization apart, let us emphasize similarity of the experimental and theoretical distributions in Figs 8,9. The same results from the data in Tables 3,4.

Table 3.

The average characteristics of π^--mesons produced in interactions of nuclei with momentum 4.2•A GeV/c with carbon nuclei (the experimental data are from the paper[27])

		$\langle p_{Lab} \rangle$	$\langle \theta^* \rangle$	$\langle p_T \rangle$	$\langle y \rangle$
pC	exp.	0.53 ± 0.03	49.4 ± 1.7	0.255 ±0.008	0.85 ±0.04
	th.	0.48	47.0	0.215	0.72
dC	exp.	0.58 ± 0.03	44.2 ± 1.0	0.256 ±0.005	1.00 ±0.02
	th.	0.54	45.8	0.227	1.00
αC	exp.	0.63 ± 0.03	43.2 ± 1.1	0.255 ±0.006	1.04 ±0.03
	th.	0.56	41.1	0.222	1.08
CC	exp.	0.62 ± 0.03	40.0 ± 0.7	0.250 ±0.004	1.1 ±0.02
	th.	0.60	40.8	0.230	1.11

Table 4.

The average characteristics of π^--mesons produced in interactions of nuclei with momentum 4.2•A GeV/c with tantal nuclei (the experimental data are from the paper[26])

		$\langle p_{Lab} \rangle$	$\langle \theta^* \rangle$	$\langle p_T \rangle$	$\langle y \rangle$
dTa	exp.	0.46 ± 0.01	0.99 ± 0.02	0.24 ± 0.01	0.70 ± 0.01
	th.	0.43	1.03	0.22	0.76
αTa	exp.	0.50 ± 0.02	0.91 ± 0.02	0.26 ± 0.01	0.76 ± 0.02
	th.	0.47	1.02	0.23	0.80
CTa	exp.	0.48 ± 0.01	0.90 ± 0.01	0.24 ± 0.03	0.79 ± 0.01
	th.	0.51	0.96	0.23	0.88

On the whole, one can conclude that the presented generalisation of DPM, showing itself to advantage when interpretating high energy data, allows one to describe the characteristics of inelastic nucleus-nucleus interactions at medium energy (with an accuracy to absolute normalization). One can hope that the subsequent development of the model - taking into account rescattering of the recoil nuleons and Fermi motion - allows essential improvement of theoretical description. To our opinion, the reached DPM accuracy allows it to be used on equal foot with the cascade model for calculating, for example, the characteristics of nuclei interactions with matter.

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Полянски А., Шмаков С.Ю., Ужинский В.В. E2-88-793
Описание неупругих ядро-ядерных взаимодействий
при промежуточных энергиях в рамках
дуальной партонной модели

Показано, что дуальная партонная модель, учитывающая процессы дифракционной диссоциации в состоянии с малой массой и конечноэнергетические поправки к асимптотическим правилам разрезания Абрамовского - Грибова - Канчели, позволяет удовлетворительно описать имеющиеся экспериментальные данные по адрон-ядерным и ядро-ядерным взаимодействиям при промежуточных энергиях.

Работа выполнена в Лаборатории вычислительной техники и автоматизации ОИЯИ.

Препринт Объединенного института ядерных исследований. Дубна 1988

Polanski A., Shmakov S.Yu., Uzhinskii V.V. E2-88-793
Description of Inelastic Nucleus-Nucleus
Interactions at Medium Energies Using
Dual Parton Model

It is shown that the dual parton model, taking into account the processes of diffraction dissociation to the low-mass states and finite energy corrections to the asymptotic Abramovski - Gribov - Kancheli cutting rules, allows satisfactory description of existing experimental data on hadron-nucleus and nucleus-nucleus interactions at medium energy.

The investigation has been performed at the Laboratory of Computing Techniques and Automation, JINR.

Preprint of the Joint Institute for Nuclear Research. Dubna 1988