СООБЩЕНИЯ
ОБЪЕДИНЕННОГО
ИНСТИТУТА
ЯДЕРНЫХ
ИССЛЕДОВАНИЙ

Дубна

E2-95-296

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ESTIMATION OF NUCLEAR DESTRUCTION IN HIGH ENERGY NUCLEUS-NUCLEUS INTERACTIONS

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1995

1 Introduction

During the last few years there were some successful attempts to describe the hadron-hadron elastic scattering at low and intermediate energies (below $1-2$ GeV) within the quark-gluon approach (see Refs. [1] - [4]). In Ref. [1] -[4] the amplitudes of $\pi\pi-$, $K\pi-$ and $NN-$ scattering were found and an agreement of the theoretical calculations with corresponding experimental data was reached at the assumption that in the elastic hadron scattering one-gluon exchange with the following quark interchange between hadrons takes place (see fig. 1a). At high energies two-gluon exchange appropriation (fig.1b) works quite well (see Ref. [5], [6] and [7], [8]). What kind of exchanges can dominate in hadron-nucleus and nucleus-nucleus interactions?

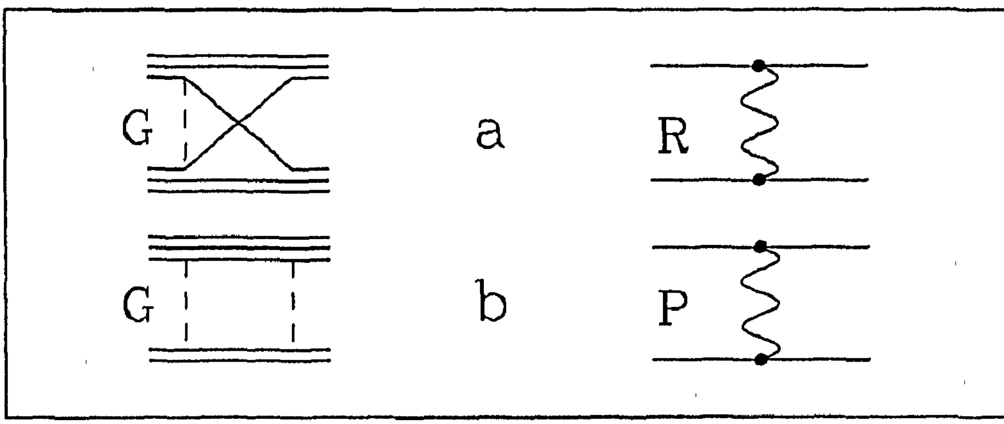

Fig. 1

The simplest possible diagrams of the processes with three nucleons are given on Fig. 2. A calculation of their amplitudes according to Refs. [1]-[4] is a serious mathematical problem. It can be simplified if one takes into account an analogy between quark-gluon diagrams and reggeon diagrams: the quark diagram of fig. 1a corresponds to a one-nonvacuum-reggeon exchange diagram; the diagram of fig. 1b describes the pomeron exchange in the $t-$ channel; the diagram of fig. 2a is in a correspondence with the enhanced reggeon diagram of the pomeron splitting into two non-vacuum reggeons. The three pomeron diagram (fig. 2d) represents the more complicated process. It is rather hard to find a correspondence between the reggeon diagrams and the diagrams of fig. 2b, 2c.

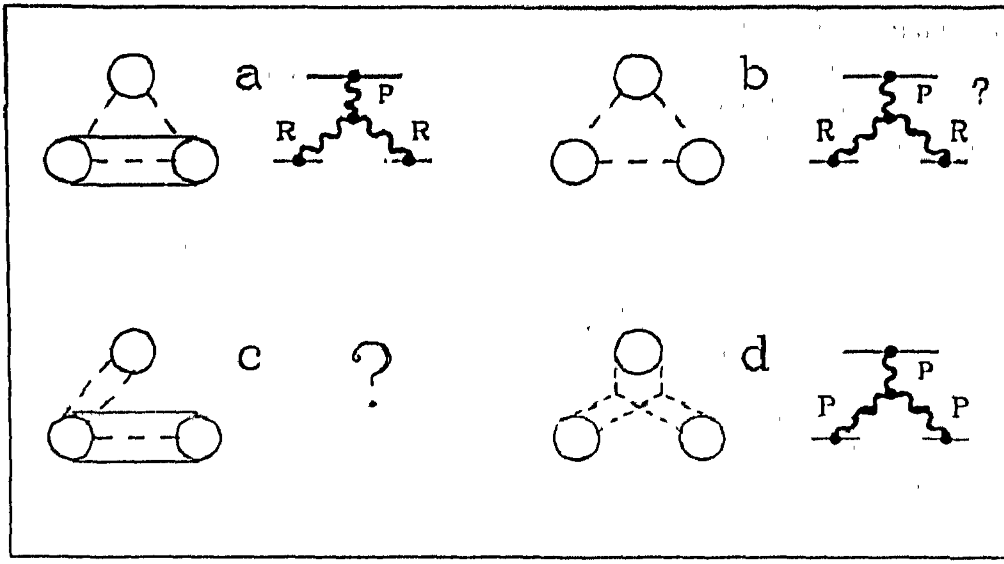

Fig. 2

The reggeon parameters and the functional forms of the amplitudes of 3-reggeon processes are well known. The constants of the reggeon interaction vertexes are poor determined. The 3-pomeron vertex constant G_{PPP} is well established ($G_{PPP} = 1.35^{-2}(GeV)^2$, Ref. [9]). There are only old data [10] and the estimations of Ref. [11] on the values of other constants - G_{PRR} and G_{RRR} which are large. Nevertheless, we believe that the properties of the reggeon amplitudes must be taken into account at the consideration of the nuclear destruction.

It is obvious that the processes like one on Fig. 2d cannot dominate in the elastic hadron-nucleus scattering because they are accompanied by a production of a high mass diffraction beam of the particles in the intermediate state. Thus, their yields are dumped by a nuclear form-factor. According to the same reason, the yields of the processes like ones on Figs. 2a, 2b can be small too. If it is not so, one will expect a large corrections to Glauber's cross-sections. The practice shows that the corrections to the hadron-nucleus cross-sections must be lower than 5 - 7 %.

The yield of the diagram of Fig. 2c gives a correction to Glauber's one-scattering amplitude. The analogous corrections must be to the other terms of Glauber's series. A sum of the corrections must lead to small effects in the elastic small angle scattering because the corrections are large at small impact parameters. So, they can manifest themselves at large scattering angles. We assume that they have a big influence on the inelastic process characteristics, too.

According to the reggeon theory, a description of the inelastic reactions can be reached at a consideration of the different cuts of the reggeon diagrams. Here the Abramovski - Gribov - Kancheli cutting rules [12] are used very often. The corrections to them were discussed in Ref. [13] in an application to the problem of particle cascading on the nucleus. As was shown in Ref. [13], a summation of the yields of enhanced diagrams allows one to describe an increase of the one-particle spectra in the target fragmentation region. At the same time the authors of Ref. [13] did not take into account the shadowing effects considered in Ref. [14].

Here we have to note that the yields of the diagrams like that shown on Fig. 2c have no shadowing corrections. The yield of the enhanced diagram of Fig. 2a has a form

$$Y_a \sim exp[-(\vec{b}_1 - \vec{b}_2)^2/3r_a^2 - (\vec{b}_1 - \vec{b}_3)^2/3r_a^2 - (\vec{b}_2 - \vec{b}_3)^2/3r_a^2]$$

where $\vec{b}_1, \vec{b}_2$ and $\vec{b}_3$ are the impact coordinates of the nucleons. At the same time, the yield of the diagram of Fig. 2c according to Refs. [1] - [4] is given by

$$Y_c \sim exp[-(\vec{b}_1 - \vec{b}_2)^2/r_c^2] exp[-(\vec{b}_2 - \vec{b}_3)^2/r_c^2].$$

In the limit of $r_a^2, r_c^2 \ll R_A^2$, where R_A is a nucleus radius, the yields coincide. Thus, we can save the results of Ref. [13] considering them as a summation of the yields of the quark-gluon diagrams.

Let us note that neither Y_a, nor Y_c depend on the longitudinal coordinates or on the multiplicity of produced particles. It is the main difference between "reggeon cascading" and "usual" cascading.

As well known, the intra-nuclear cascade model (CEM) ([15]-[20]) assumes that in a hadron-nucleus collision the secondary particles are produced due to an inelastic interaction of the projectile particle with a target nucleon. The produced particles can interact with other target nucleons. A distribution on a distance l between the first interaction and the second one has a form

$$W(l)\, dl \sim \frac{n}{<l>} exp(-\frac{n}{<l>} l),$$

where $<l> = 1/\sigma\rho_A$, σ is a hadron-nucleon cross-section, n is the multiplicity of the produced particles and $\rho_A \simeq 0.15 fm^{-3}$ is the nuclear density. At the same time the amplitudes or the cross-sections of the processes shown on Fig. 2 have no dependence on l or n. Thus, we expect that in the quark-gluon or reggeon approach the "cascade" will be more restricted than it is in the cascade model. The difference between approaches can lead to the different predictions for the light nuclei destruction (an effect of the limited volume) and for the characteristics of the heavy nuclei interactions (an influence of a large multiplicity of the produced particles).

To show this, we first of all give in Sec. 2 a simple method to estimate the nuclear destruction in the framework of the quark-gluon approach. We apply it to an analysis of the experimental data in Sec. 3 where the cascade model calculations will be presented, too. There we concentrate on the characteristics of the spectator part of the nucleus. The simplest characteristic of such type studied in many photoemulsion experiments is a distribution on the sum of spectator fragment charges. It was before described in the paper [21].

The distributions on the summered charge of spectator fragments with charges greater than 2 were obtained at ALADIN experiment [22] - [25]. At their interpretation within the framework of the cascade model with an account of the nuclear multifragmentation the authors of Ref. [26] met some difficulties. They left the cascade model and used a phenomenological parametrization for a distribution on the excitation energy and the mass number of the residual nucleus. It is an evidence that there is no any successful model of nuclear destruction in nucleus-nucleus interactions above $200 - 300$ MeV/nucleon. Below we will show that our proposed method gives an opportunity to estimate the distribution on mass, charge and excitation energy of the residual nucleus. It can be used at intermediate as well as at high energies.

At the experiments of E-802 collaboration [27, 28] the distributions on the energy in the zero-degree-calorimeter (T_{ZDC}) for the interactions of $Si + Al, Cu, Ag, Au$ at energy 14 GeV/nucleon were measured. The analogous distributions were determined at CERN experiments [29] for the interactions of $O + C, Cu, Ag, Au$ at 60 GeV/nucleon. The latter were described in the FRITIOF model [30]. Having no opportunity to take the experimental conditions into account exactly, we assume that the distribution on T_{ZDC} is a distribution on a sum of spectator fragment energies. Nevertheless, we reach the better agreement of our calculations with the experimental data than the FRITIOF model does. Thus, we dare to give our estimations for the impact parameter and for the number of intra-nuclear collisions of the evens with different values of T_{ZDC}.

2 A model of nuclear destruction at fast stage of the interaction

At first glance, the interaction between the second and third nucleons in the process of Fig. 2c is an elastic rescattering of the second nucleon on the spectator nucleon. Thus, it seems that the intra-nuclear cascade can be simulated by a cascade of elastic and inelastic interactions of the ejected nucleons developed in the 3-dimensional space of the nucleus. The standard cascade-evaporation model assumes that there are additional interactions of the produced nucleons with target nucleons. As the produced particles possess closed coordinates, there must be a strong shadowing of the particles by each other. A practice of study of the nucleus-nucleus interactions shows that the cross-sections are mainly determined by the geometrical aspects, especially by nuclear sizes. So, one can assume that in the hadron-nucleus collision a cross-section of the bunch of the particles produced at the first interaction is near to the $NN-$ interaction cross-section. From this point of view, it seems it is not extra-ordinary to suppose that only the ejected nucleons can suffer the interactions. It is obvious that according to the approach the ejected nucleons must lose their energies in the secondary interactions and the momentum distribution of the nucleons in the central collisions must be softer than it is in the peripheral ones. The experiment [31] shows an inverse tendency.

In the reggeon approach another situation is possible. According to the parton model a hadron is surrounded by a cloud of the virtual parton fluctuations which can fuse or split. If the mean life time of a fluctuation is of odder τ then when a fast hadron with velocity $v \gg R_A\sqrt{1-v^2}/\tau$ penetrates the nucleus different fluctuations can interact with different nuclear nucleons. As the nucleons taking part in the interactions are in the equal conditions, we cannot expect the softening of the spectra. Thus, we consider the mentioned experimental data as an indication of the reggeon scenario.

Unfortunately the reggeon method of the calculation and the summation of the yields of the enhanced diagrams of the hadron - nucleus and nucleus - nucleus interactions is not developed enough for practical tasks. Thus, we are forced to formulate a phenomenological model of particles cascading into the nucleus in order to estimate the nuclear destruction, because the nuclear destruction is used at the experimental study as a criteria for selection of different types of the inelastic interactions, for example, central and peripheral ones.

The model formulation:

1. As it was said above, the "reggeon cascade" is developed in the space of the impact parameter. Thus, for its description it is needed to determinate a probability to involve a nucleon into the "cascade". It is obvious that the probability depends on a difference of the impact coordinates of the new and previous involved nucleons. Looking at the yield of the diagram of Fig. 2c, we choose the functional form of the probability as

$$P(|\vec{b}_i - \vec{b}_j|) = Cexp(-(\vec{b}_i - \vec{b}_j)^2/r_c^2). \qquad (1)$$

   Here $\vec{b}_i$ and $\vec{b}_j$ are projections of the radiuses of i^{th} and j^{th} nucleons on the impact parameter plane.

2. The "cascade" is initiated by the primary involved nucleons. If the constant C is small we can use the Glauber theory for their determination.

3. We assume that all involved nucleons are ejected from the nucleus.

The "cascade" looks like that: a projectile particle interacts with some of the intra-nuclear nucleons. They are called "wounded" nucleons. The wounded nucleons initiate the "cascade". A wounded nucleon can involve a spectator nucleon into the "cascade" with the probability (1). The latter one can involve the second nucleon. The second nucleon can involve the third one and so on.

A Monte Carlo algorithm for estimation of the nuclear destruction in the nucleus-nucleus interactions, which corresponds the model formulation, includes the following steps:

1. The calculation of the impact parameter distribution within the framework of the Glauber theory [32];

2. The sampling of the impact parameter and the nucleon coordinates;

3. The determination of the wounded nucleons (see Ref. [32]);

4. The determination of the spectator nucleons involved in the "cascade" by the wounded nucleons. If the number of the involved nucleons is equal to zero - exit;

5. If the number of the involved nucleons is not equal to zero, a possibility is considered to involve the other spectators nucleons by the involved ones. If the number of the new involved nucleons is equal to zero - exit. In other case - it is needed to repeat the step 5 taking into account only the new involved nucleons.

The first step is performed only once at the given mass numbers of the projectile and target nuclei. The steps 2 – 5 are repeated until the needed statistics is reached. The steps 4, 5 are applied to the nucleons of projectile and target nuclei.

3 The choice of the model parameters

The allowed region of the model parameters C and r_c was determined in Ref. [21] at fitting the experimental data on the high energy proton-nucleus interactions [33]. It is presented on Fig. 3.

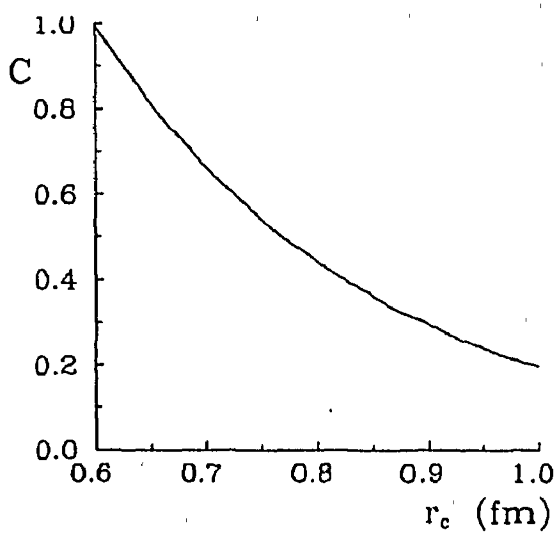

Fig. 3

The authors of Ref. [21] reached an agreement with the experimental data on g-particle multiplicity distributions in nucleus-nucleus interactions at $C = 1$ and $r_c = 0.6$ fm. The authors of Ref. [21] pointed out that the agreement can be obtained at other values of the parameters from the allowed region. In order to specify the parameters and to check the possibility of the model, we turn to ALADIN data on the gold interactions with nuclei at 600*A MeV.

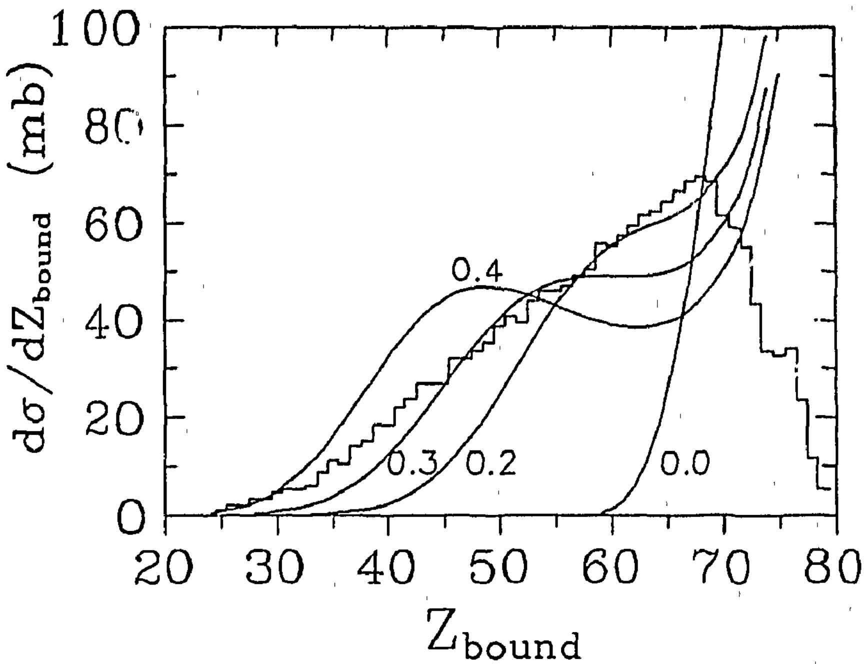

Fig. 4

On Fig. 4 the experimental distribution [26] on "bounded" charge in the $^{197}Au + ^{12}C$ interactions (histogram) is presented in a comparison with the model calculations (solid lines) at the different values of C and r_c (the values of C are given by the numbers at the curves). At the experiment the "bounded" charge is determined as $Z_{bound} = \Sigma_F Q_F$ where the sum runs over the gold spectator fragments having a charge greater or equal 2. At the given stage of our study when we don't consider the nuclear multifragmentation and evaporation we fail to separate one-charged fragments. So, our calculations represent the distributions on the charge of the residual nucleus. The variant with $C = 0$ corresponds to the pure Glauber approximation. As one can see, the Glauber approach cannot describe the nuclear destruction. The variant with $C = 0.2$ is best of all. We hope that the one-charged fragment selection will shift the curve to the left. The variants with $C \geq 0.3$ are rejected because the corresponding curves have the dips in the region $Z_{bound} \sim 55 - 70$.

On Fig. 5 we present our calculations at $C = 0.2$ and $r_c = 1$ fm for the $Au + C, Cu, Pb$ interactions (solid lines) in the comparison with the experimental data [26] (histograms). Of course, it is very hard to talk about the agreement. But we fix that the calculations have the same tendency as the experimental data do. Thus, we believe that the proposed model can be served as a base for a more realistic model of the nucleus - nucleus interactions at the intermediate energies.

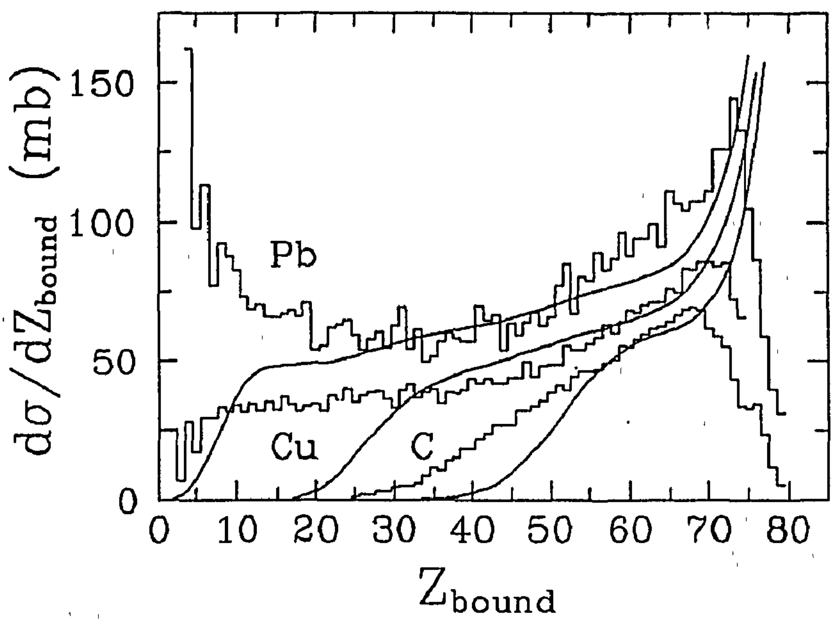

Fig. 5

It is interesting to compare the experimental data with the cascade model calculations presented on Fig. 6. At the calculations we used the version of the cascade model described in Ref. [34]. The model takes into account the trailing effect, Pauli principle, the dependence of the Fermi momentum on the local nuclear density, the pre-equilibrium emission and the evaporation of the nuclei. On Fig. 6 a distribution on the charge of the residual nucleus after fast cascade stage is presented by solid circles. The light points show a distribution on Z_{bound} after the pre-equilibrium decay. At last the solid curve presents a distribution on Z_{bound} after the evaporation stage. The experimental data are shown by a histogram.

As one can see, the distribution after the cascade stage has no bright peculiarity. The pre-equilibrium emission shifts the distribution on the left and leads to a dip in the region of $Z_{bound} \sim 45$. The small fluctuations, which are not caused by the statistic, appear at $Z_{bound} \sim 55 - 75$. The large fluctuations after the evaporation stage reflect the shell corrections to the binding energy of the nuclei [1]. Without the shell corrections the distribution has no structure (see dashed curve on Fig. 6).

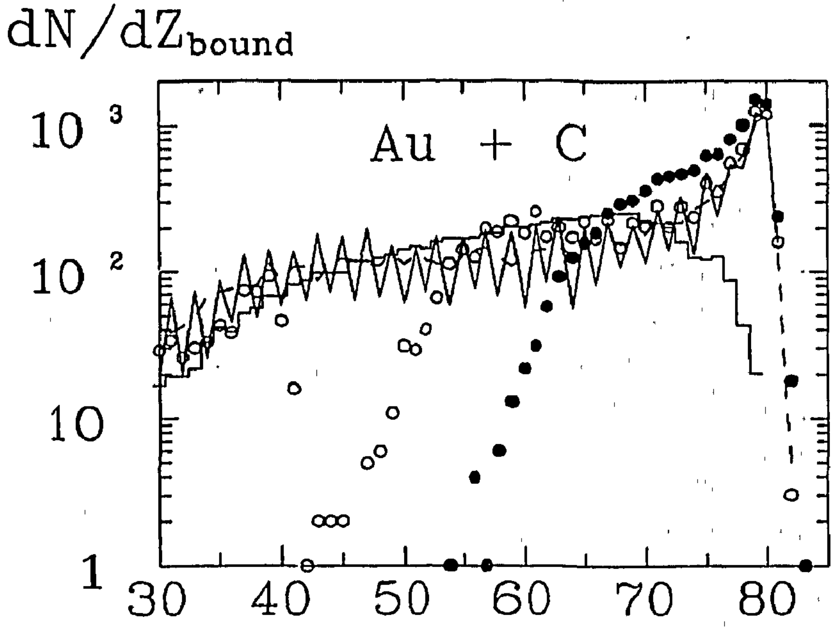

Fig. 6

The lower influence of the shell corrections is quite natural at high nuclear temperature. So, an absence of the fluctuations in the experimental data point out on the hot nuclei formation in the nucleus-nucleus interactions. As follows from our calculations, it is not enough to take into account the pre-equilibrium emission and the evaporation processes in the framework of the standard cascade-evaporation model. Let us mark that according to the calculations the appearance of the fluctuations is connected with a large excitation energy of the nuclear residual. Decrease of the energy going from $Au+C$ interactions to $Au+P$ interactions leads to decreasing the magnitude of the fluctuations. We think the magnitude of the fluctuations can be a measure of the excitation energy and a disappearance of the fluctuations can manifest the multifragmentation of the nuclei[2].

[1]The authors are thankful to S.Yu. Shmakov for a discussion of the question

[2]This interesting suggestion was proposed by Prof. F.A. Gareev.

It is a pity that the restricted resources of our computer time did not give us an opportunity to perform the cascade calculations for heavy target nuclei.

Let us go to the light nuclei destruction. On Fig. 7 the experimental distributions on the energy in the zero-degree calorimeter [27, 28] (histograms) are presented in a comparison with the cascade model calculations (points). As one can see, CEM reproduces the gross features of the data. Only at $T_{zdc} < 100$ GeV there is a discripance between the calculations and the data. As we had no opportunity to take the experimental conditions into account exactly, we plotted on the figure the distributions on the energy of the residual nuclei. The account of the produced mesons will shift the distributions to the right. To sum it up, we conclude CEM predicts too large destruction of the projectile ^{28}Si nuclei in 15% of the interactions. So, CEM cannot be used for the estimation of the characteristics of the central collisions.

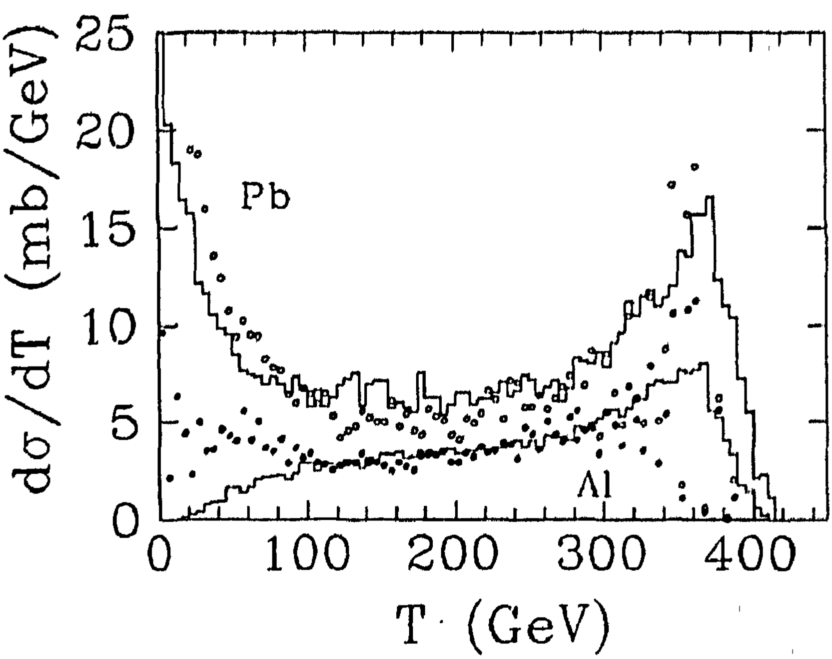

Fig. 7

On Fig. 8 we present the calculations performed in the framework of our model (solid lines) in comparison with the experimental data (histograms). As one can see, the model describes the strong destruction of the light nuclei in the interactions with light and heavy target nuclei. We hope to reach the better agreement at large values of T_{zdc} after including the nucleon Fermi motion and taking into account the experimental conditions.

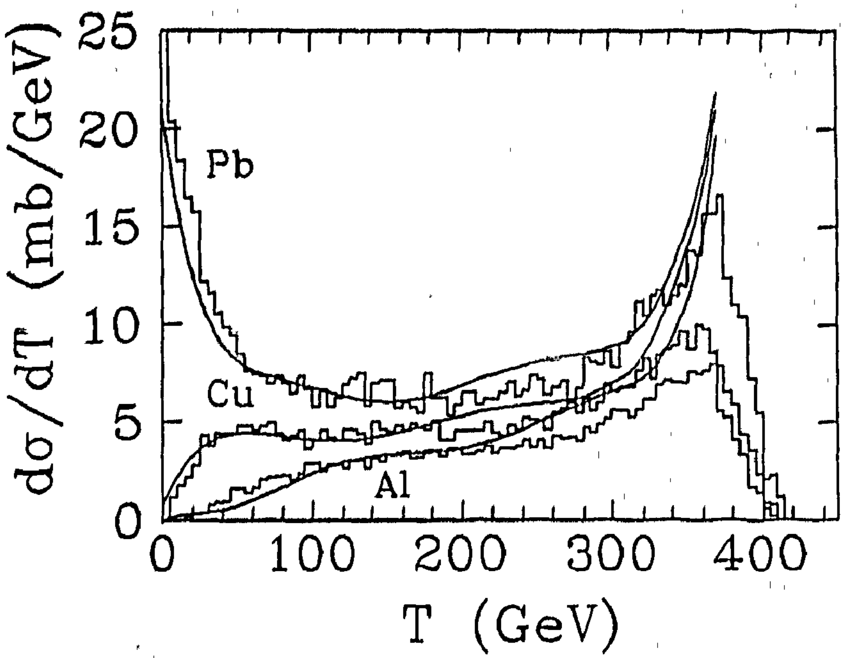

Fig. 8

For the current experiments at BNL we give the characteristics of $Au + Au$ interactions at 10 A GeV on Fig. 9, 10. We believe they will be useful at the future comparison of the different model predictions with the data on multi-particle production in the central collisions.

For calculation of the excitation energy one can use an assumption that each spectator nucleon placing at the distance less than 2 fm from a nucleon touched at the fast stage of the interaction receives an energy distributed as

$$P(\epsilon)d\epsilon = \frac{1}{<\epsilon>} e^{-\epsilon/<\epsilon>} d\epsilon.$$

A sum of the energies transferred to the spectator nucleons gives the excitation energy. The quantity $<\epsilon>$ is treated as a fitting parameter. The preliminary value of $<\epsilon>$ is 10 MeV.

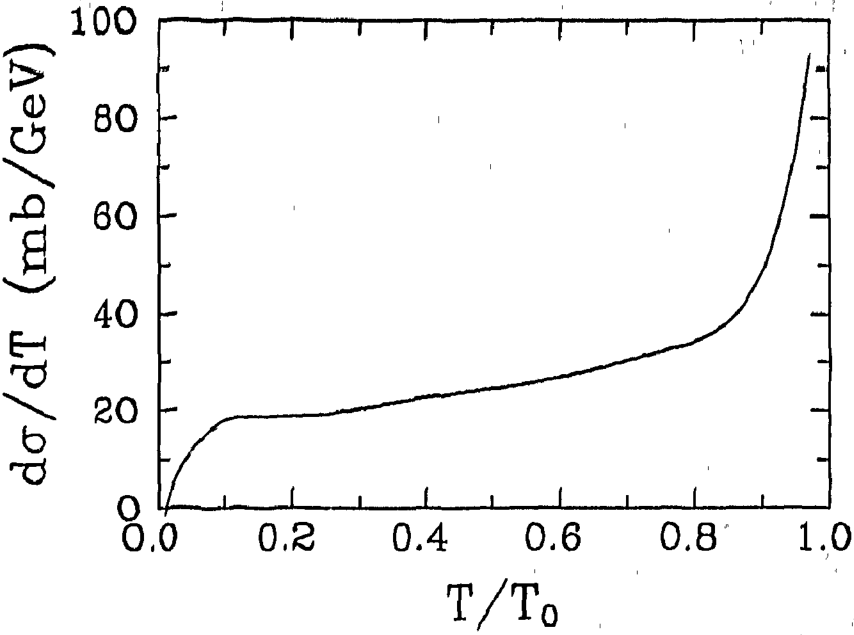
dσ/dT (mb/GeV)
100
80
60
40
20
0
0.0
0.2
0.4
0.6
0.8
1.0
T/T0

Fig. 9

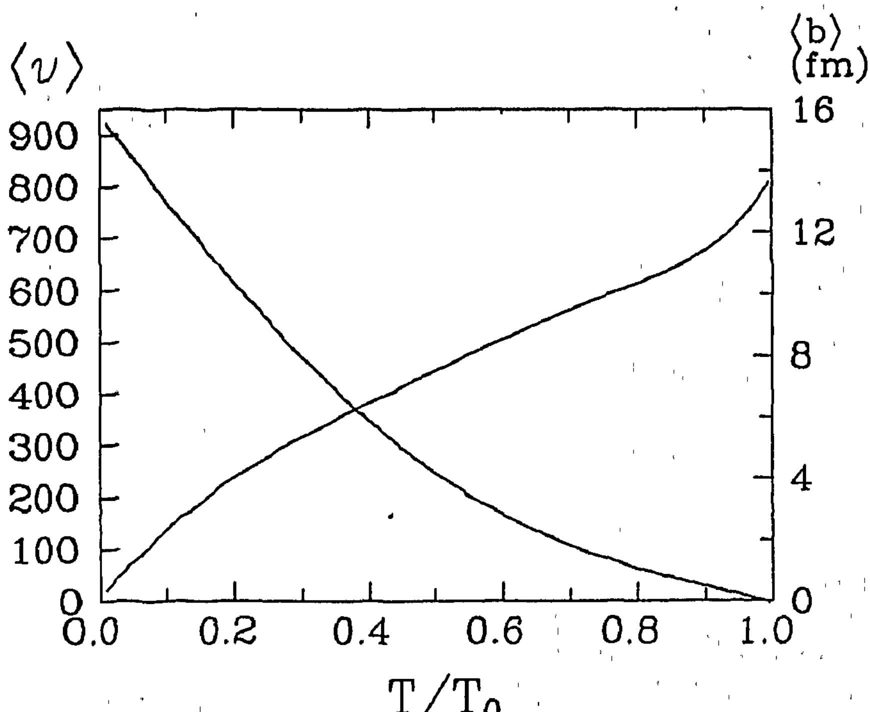
⟨ν⟩
⟨b⟩
(fm)
900
800
700
600
500
400
300
200
100
0
16
12
8
4
0
0.0
0.2
0.4
0.6
0.8
1.0
T/T0

Fig. 10

At last we give the description of CERN data on ^{16}O interactions with nuclei at 60 GeV/nucleon. On Fig. 11 the data of Ref. [29] (points) are presented in comparison with FRITIOF calculations (dashed lines).

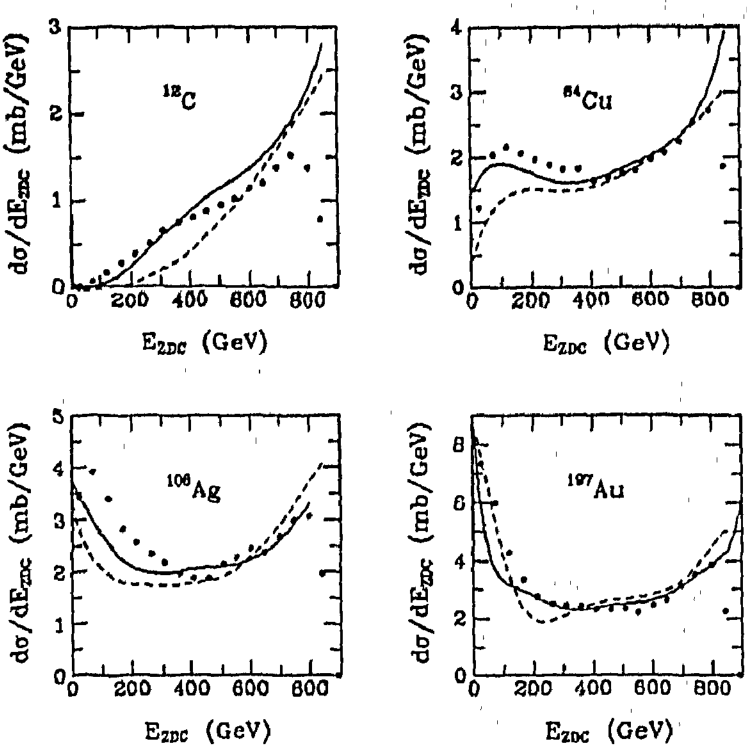

Fig. 11

Our calculations are given by solid lines. As it was before, we did not take into account the experimental conditions, the Fermi motion of the nucleons, and the influence of the produced particles. All of these factors were considered at FRITIOF calculations. Nevertheless, we reproduce the data better than FRITIOF does.

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Received by Publishing Department
on July 7, 1995.