Analysis of hadron production in nucleus-nucleus interactions up to and out of kinematical limit of free NN-collisions in the frame of FRITIOF model

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In the framework of the modified FRITIOF model, the inclusive spectra of the cumulative $\pi^0$, $\pi^-$-mesons and protons produced in the nucleus-nucleus interactions at 4.5 GeV/c/nucleon and 4.2 GeV/c/nucleon are calculated. It is shown that the model reproduces qualitatively, and in some cases quantitatively the main experimental regularities of $\pi$-mesons production, and ”soft” part of the proton spectra. According to the model the production of the cumulative particles is connected with the mechanism of the ”soft” nucleon-nucleon interaction.

The production of particles in hadron-nucleus and nucleus-nucleus interactions in the kinematical region forbidden for free hN-collisions (so-called cumulative processes) is one of the main sources of information about the nuclear structure function and the multi-particle production mechanism. This kinematical region corresponds to the Feynman variable $X_F > 1$ (with respect to a single NN-interaction). $X_F = 2p_l^*/\sqrt{S}$, where $p_l^*$ is the longitudinal momentum, $\sqrt{S}$ is the total energy of NN-interaction in the nucleon-nucleon center of mass system.

The cumulative phenomena predicted by A.M. Baldin [1] were discovered by the group of Stavinski [2] in early seventies, and have been intensively investigated during last thirty years. The wide experimental and theoretical study caused numerous models for explanation of this interesting phenomenon. The main property of all models is the existence of massive (heavier than nucleon) compact object on which the creation of cumulative particle is occurred. In dependence on this object creation all models can be divided into the ”hot” [3] and ”cold” [4], [5] models. The models for explanation of the cumulative processes have analytical form and can pretend on a description of restricted kinematical region. The reproduction of their results are quite complicated.

At the same time, there are created the phenomenogical Monte Carlo generators of events with easily reproduced results. But the cumulative production of particles isn’t assumed directly in the code-generators. It is needed to note that ”hot” models ideas have found an extraordinary application in high energy physics in some modified forms. They are used in the well-known models of multi-particle production such as FRITIOF [6], RQMD [7], and HIJING [8]. The common assumption of the models is that the soft inelastic hadron-hadron collisions have a binary character $a + b \rightarrow a' + b'$, where $a'$ and $b'$ are excited hadrons. The excited hadrons with masses $m_{a'}$, $m_{b'} > m_a$, $m_b$ are considered as QCD-strings, and LUND-model [10] is used to describe their decays.

In the case of hadron-nucleus interactions, the models assume that an excited hadron $a'$ can collide with other nuclear nucleons and increase its mass. The same can take place in nucleus-nucleus interactions.

As one can easily notice, that the general representation of the hadron-nucleus interactions assumed by the models is almost similar to that considered in Ref. [3]. The authors of Ref. [3] supposed that heavy hadron system (a fireball) which does not include a leading particle is created in the first collision of projectile hadron with a nuclear nucleon. The fireball moving in the nucleus collides with other nucleons, slows
down, and increases its mass. As a result, a production of particles in the regions kinematically forbidden in free hadron-nucleon collisions becomes possible. Thus, one can expect that the cumulative particles have to appear in the models, in particular, in the FRITIOF model.

Figures 1, 2 show the experimental data [11] on fast $\pi^0$-mesons production in nucleus-nucleus interactions at $P = 4.5$ A GeV/c with FRITIOF model calculations taking into account the last corrections [12]. As seen, the FRITIOF model predicts the cumulative particle production.

\[ (E/A) d\sigma (d^3p)/dE d\Omega \]

\[ \theta_{\pi} \leq 16^\circ \text{ and } E_{\pi} \geq 2 \text{ GeV} \]

\[ \text{In fig. 1, the experimentally measured invariant cross-sections of } \pi^0\text{-meson production per mass number of projectiles } (A_p) \text{ as a function of cumulative number } X \text{ are} \]

Figure 1: Invariant inclusive cross-sections of $\pi^0$-meson production in nucleus-nucleus interactions at 4.5 GeV/c/nucleon. The points are experimental data of the FOTON setup, histograms are the FRITIOF model calculations.
presented by circles. The variable $X$ was determined as

$$X = \frac{m_N E_{\pi^0} - m_{\pi^0}^2/2}{E_N m_N - E_N E_{\pi^0} - m_N^2 + P_N P_{\pi^0} \cos \theta_{\pi^0}},$$

where $m_N$ and $m_{\pi^0}$ are nucleon and meson masses, respectively, $P_N$ is the momentum of projectile per nucleon ($P_N = 4.5$ GeV/c). $P_{\pi^0}$ is $\pi^0$ momentum, $E_N = \sqrt{M_N^2 + P_N^2}$, $E_{\pi^0} = \sqrt{m_{\pi^0}^2 + P_{\pi^0}^2}$. The systematic errors of the cross-section is about $\sim 20\%$. The statistical errors are in the circle limits.

In fig. 1, histograms demonstrate calculations of the cross-sections of $\pi^0$-mesons production at $E_{\pi^0} \geq 2$ GeV and $\theta_{\pi^0} \leq 16^0$ performed within the framework of FRITIOF model. The calculation results are normalized on the nucleus-nucleus interactions cross-sections obtained in Glauber approach [13]. As seen, the slopes of experimental and the calculated curves are close, but the calculated cross-sections overestimate the experimental values 2-3 times.

Figure 2: Differential inclusive cross-sections of $\pi^0$-meson production in nucleus-nucleus interactions vs transverse momenta at 4.5 GeV/c/nucleon. The notation is identical to that in fig. 1.

Fig. 2 illustrates a better agreement between the calculations and the experimental data. Fig. 2 gives the invariant cross-sections of $\pi^0$-mesons production with respect to
the $\pi^0$-meson transverse momentum. The model reproduces both the spectrum forms and the absolute values of the cross-sections. The reason of such different descriptions of the experimental data of fig. 1 and fig. 2 is not clear for us.

The model FRITIOF allows one to decipher the cumulative particle production mechanism in detail. The different characteristics of $CC$-interaction events accompanied by the fast $\pi^0$-meson production are presented in fig. 3. Fig. 3a shows the yields into the invariant inclusive cross-section of projectile and target nucleons (dashed and dotted curves, respectively). The relative yields are given in fig. 3c. As seen, the contribution of the target nucleons is about $\sim 25\%$.

Figure 3: Various characteristics of $CC$-interactions at 4.5 GeV/c/nucleon with fast $\pi^0$-meson production.

Fig. 3d shows the average longitudinal momenta of projectile nucleons before and after the interaction (solid and dashed curves, respectively). According to the figure, more and more energetic projectile nucleons are selected with increase the cumulative number. Accounting the Fermi-motion is not critical for the description of the inclusive cross-sections because without the Fermi-motion the cross-section in the region of $X \sim 0.9 - 1.3$ does not decrease in needed quantity, the slope of the cross-section is only changed (see fig. 4). It is natural that the longitudinal momenta of projectile nucleons decrease during the interaction, but this takes place below $X \sim 1.5$ (see fig. 3d). The nucleons acquired the momenta larger than average momenta of incident nucleons, give
the contribution into the fast $\pi^0$-meson production in the region of large $X$. It is clearly seen in the calculations performed without taking the Fermi-motion into account (see insert in fig. 4, where the solid line shows the longitudinal momenta of projectile nucleons before the interaction, dashed line shows the same after the interaction with the fast $\pi^0$-meson production). The considered effect of the nucleon acceleration is a specific feature of the assumed nucleus-nucleus interaction mechanism.

The presented results allow one to expect a description of spectra of charged particles produced in nucleus-nucleus interactions up to and out of kinematical limit of free NN-collisions.

To test the possibility of applying model FRITIOF for reproduction of the characteristics of cumulative charged particles, we consider the experimental data on $\pi^-$
-meson production in backward hemisphere [15]. In the fig. 5 we present the invariant inclusive cross-sections of the $\pi^-$-meson production in the $pC$-, $dC$-, $\alpha C$-, and $CC$-interactions at momentum of projectile 4.2 GeV/c/nucleon as a function of kinetic energy. There are shown three groups of $\pi^-$-mesons: with emission angles from $90^\circ$ to $110^\circ$, from $110^\circ$ to $130^\circ$, from $130^\circ$ to $180^\circ$.

![Graphs showing invariant inclusive cross-sections of $\pi^-$-meson production in various interactions.](image)

Figure 5: Invariant inclusive cross-sections of $\pi^-$-meson production in $pC$-, $dC$-, $\alpha C$- and $CC$-collisions. As seen from the figs. 5 and 6, the calculations in the frame of modified by V.Uzhinskii FRITIOF model [9] reproduce qualitatively (in the some case quantitatively) the dependence of the invariant cross-section of the $\pi^-$-meson production on kinetic energy, on the mass

In the fig. 6, we present the same for $dT\alpha$, $\alpha T\alpha$, and $CT\alpha$-collisions. As seen from the figs. 5 and 6, the calculations in the frame of modified by V.Uzhinskii FRITIOF model [9] reproduce qualitatively (in the some case quantitatively) the dependence of the invariant cross-section of the $\pi^-$-meson production on kinetic energy, on the mass
of projectile nucleus, on the mass of target nucleus, and on the emission angle.

Figure 6: Invariant inclusive cross-sections of $\pi^-$-meson production in $dTa$, $\alpha Ta$- and $CTa$-interactions at 4.2 GeV/c/nucleon. $T$ - kinetrical energy of $\pi^-$-mesons, $\theta$ - angle of $\pi^-$-meson production in laboratory system. The points are experimental data of the propan collaboration, histograms are the FRITIOF model calculations.

For more detail consideration, let us turn to spectra of the $\pi^-$-meson production in the $NN$, $pC$, and $CC$-interactions in the backward hemisphere [15] (fig. 7). According to the calculations, spectra of $\pi^-$-mesons in the $NN$ and nucleus-nucleus interactions are similar. The description of pion spectra in the $AA$-interactions was achieved without free, fitting parameters. In given approach, the similarity of pion spectra is explained easily. In the nucleon-nucleon collisions at sufficiently high energies, spectra in the region of target fragmentation are not dependent on the interaction energy. In the hadron-nucleus interactions, participating nucleons fragment independently on projectile particle, as in $NN$-collisions. Therefore, every participant-nucleon gives independent contribution to the cross-section. Mean multiplicity of such nucleons is proportional $<\nu> \sim A^{1/3}$. Then, the process cross-section is proportional
In the nucleus-nucleus interactions, the similarity of spectra can take place, if target nucleons collide no more than one time. The calculations show that in the considered interactions of light nucleus with light nucleus and heavy nucleus, it is really so. The spectra of mesons can be considered as similar only in the first rough approximation. More detailed consideration shows that it isn't possible to describe meson spectra in NN-collisions by simple exponent. At the same time, spectra of AA-interactions can be described by exponent quite well. The difference is caused by the interaction mechanism. It is obviously, the main distinction is so that spectra of NN-collisions are restricted by allowed kinematical region, and spectra of AA-interactions extend over this region. For presented experimental data, only last points are out of kinematical limit of free NN-interactions. According to the fig. 7 spectra of $\pi^-$-mesons change unessentially with taking into account fermi-motion of nucleus in kinematical region allowed in NN-interactions. Production of mesons without fermi-motion of nucleos out of this region is described by mechanism of the nucleon mass increase.

Let us consider dependence of the cumulative particle production cross-section on target mass number. For this let us turn to the data of dA-reaction [16] at momentum of projectile deuteron equals to 8.9 GeV/c with production of $\pi^-$-mesons at zero degree. The fig. 8 shows the cross-section as a function of variable $x$. Variable $X$ is determined as

$$x = \frac{M_N E_{\pi^-} - \frac{1}{2} M_{\pi^-}^2}{E_N M_N - E_N E_{\pi^-} - M_N^2 + P_N P_{\pi^-} \cos \theta_{\pi^-}}$$

where $M_N$, $M_{\pi^-}$, $P_N$, $P_{\pi^-}$, $E_N$, $E_{\pi^-}$ are masses, momenta and energies of nucleon and $\pi^-$-meson respectively; $\theta_{\pi^-}$ – emission angle of $\pi^-$-mesons in lab. system. In the fig. 8, the solid lines is the standard model calculation. The shape of the calculated curve is near to the experimental data, but the calculations overestimate the experimental data. The simplest way to reach an agreement between the experiment and the theory is a decrease of NN-interaction cross-section in nucleus. At the 50% decrease the calculations underestimate the experimental data (see the dashed lines), and at the 30% decrease (see the histograms in the fig. 8) we have a good agreement. The other possibility to reach the agreement is a variation of model parameters, that leads to
Figure 8: Invariant inclusive cross-sections of $\pi^-$-meson production in $dp$-interactions. The points are experimental data of the SPHERA collaboration, curves are the FRITIOF model calculations.

the change of the cross-section shape. For example, the solid lines in the fig. 8b give the calculations without de-excitation of the nucleons. At the 30% decrease of $NN$-interaction cross-section in the nucleus, we have also a good description of the cross-section dependence on target mass number.

The fig. 9 gives a ratio of deuteron-nucleus and deuteron-proton cross section. The points are experimental data at $X$ equal of 1.23 [16], the histograms are calculations. The weak A-dependence is explained by the following effect. Our calculations show

Figure 9: Ratio of cross-sections of $\pi^-$-meson production on the nucleus and on the proton at $x=1.23$. The points are experimental data of the SPHERA collaboration, curves are the FRITIOF model calculations.

that the $dA$-collisions with two NN-interactions give the main contributions to the cumulative particle spectra. In the collisions with the large number of the NN-interactions
there is not practically cumulative particles due to energy losses of projectile deuterons. In the collisions with two NN-interactions, the processes dominate where two projectile nucleons collide with one target nucleon. These processes have peripheral character.

The more complete situation takes place with a description of cumulative proton spectra. In fig. 10 the invariant inclusive cross-sections of protons emitted in backward hemisphere are presented as a function of kinetic energy. Points are propan collaboration experimental data, histograms are our calculations. The shape of the curves is determined by Fermi-motion, and the absolute values of the cross-sections is determined by nuclear destructure model. The reggeon theory inspired model of nuclear destructure is used in modified FRITIOF model. It is assumed, that each in-nuclear collision initiate reggeon exchanges in the spectator part of the nucleus. The probability to evolve spectator nucleon to the cascade is given as

\[ W(\vec{b}) = C_{nd} \exp(\vec{b}^2 / r_{nd}^2), \]

where \( b_{ij} \) is a difference between impact coordinates of the spectator nucleon and inelastic interacted nucleon. \( C_{nd} \) and \( r_{nd} \) are parameters. Fitting these parameters,
we have a good description only for the "soft" part of the proton spectra. For $AC$-interactions, we choose $C_{nd} = 1$, and $r_{nd} = 1.1 \ (fm^2)$. But for $ATa$-interactions [19], we have $C_{nd} = 0.2$ and $r_{nd} = 1.1 \ (fm^2)$ (see fig. 11).

The experimental data [17],[19] show a change of a slope of proton spectra at $T \sim 0.2 - 0.25 \ GeV$. There are not such changes in the model calculations. At the same time, we reproduce the dependence of the cross-sections on the emission angle of protons, and projectile and target mass numbers. For explanation of hard part of the cumulative proton spectra, it is needed to use the other production mechanism (for example multi-quark bags, fluctons, and so ones).

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References


