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On the hadron formation time in pion-nucleus interaction

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НАУЧНО-ИССЛЕДОВАТЕЛЬСКИЙ ИНСТИТУТ ЯДЕРНОЙ ФИЗИКИ

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Abstract

Differences in the observable characteristics of pion-nucleus interactions at high energy are investigated for two definitions ("constituent" and "yo-yo") of the hadron formation time. The Monte Carlo simulation of hadron-nucleus interactions and quark-gluon string model for hadron-hadron collisions are used. It is shown that the momentum spectrum of the protons in the target fragmentation region is most sensitive to the definition of the formation time. The inclusive meson and meson resonance spectra are similar in the both versions.

Introduction

In recent years the interest has been renewed to the problem of hadron formation time $\tau(h_f)$, or length $l(h_f)$, in the processes of strong interactions. The classical works [1-3] on this subject used quantum mechanical approach. They considered only the structureless particles. For composite particles (such as hadrons) the very notion of the formation time can be developed only on the quark-parton level [4-6]. In this case its definition becomes model dependent.

The present work is an attempt to reveal and study the manifestation of the hadron formation time in reactions on nuclear targets using the Monte Carlo simulation of hadron-nucleus interactions and the realistic quark-gluon string model (QGSM) for the description of hadron-hadron collisions [7-10]. The particular attention is paid to the question, what measurable characteristics are most sensitive to the choice of the formation time (length) definition.

We use two definitions of formation length considered by A. Bialas and M. Gyulassy [11] in the framework of the Lund string model [12,13]: the "yo-yo" ("y") and "constituent" ("c") one. The distinctions between them are connected with the different definitions of the hadron h_f formation point $\vec{r}_{form}=(\vec{b}_{form},z_{form})$ (the z-axis is along the beam direction) and, therefore, with the different dependence of the formation length l upon the hadron momentum.

In "y" representation this coordinate corresponds to the first intersection point of trajectories of quarks (constituents) $\vec{r}^{\,y}_{form}$, and in "c"-representation to the coordinate $\vec{r}^{\,c}_{form}$ of the string break point after the act of string production (Fig. 1a). These definitions are extreme because it is possible also to introduce "intermediate" definitions as it was done for example in paper [14].

The distributions $D_y(x,l,L)$ and $D_c(x,l,L)$ of these coordinates, where l is the distance from the point of hadron interaction $\vec{r}_{int}$ to the point of hadron formation, and x is a fraction of the maximum light-cone

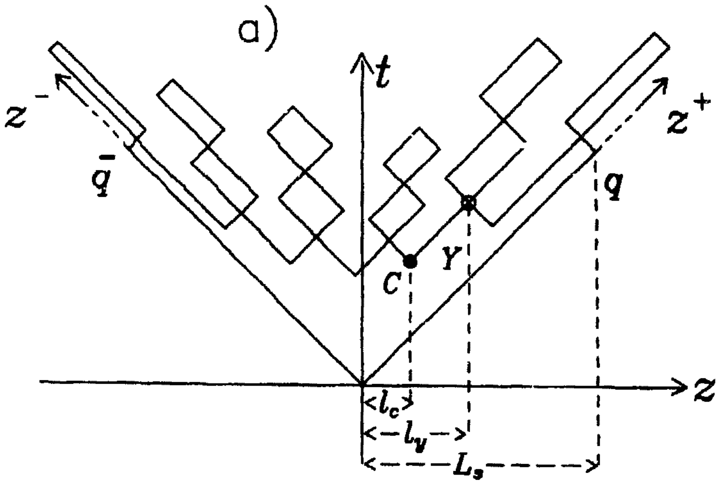

Fig. 1a. The space-time development of the string decay: "constituent" (l_c) and "yo-yo" (l_y) hadron formation length.

momentum of the quark carried away by the hadron, are quite different for the two versions [11,15]. In particular, the mean formation length

$$\langle l_{c,y}(x)\rangle = \int_0^L dz\, z\, D_{c,y}(x,z,L) \,/\, D_{c,y}(x,L)$$

behaves differently at $x \to 1$: $\langle l_y(x)\rangle/L \to 1$ and $\langle l_c(x)\rangle/L \to 0$, where L is the total string length (Fig. 1b).

Obviously, on the hydrogen target all the observable characteristics for two versions "c" and "y" are the same. Only subsequent interactions provide the possibility to find out the differences in the shape of the distributions $D_c(x,l,L)$ and $D_y(x,l,L)$. The subsequent interactions of strings and new hadrons, produced in their decays, with the nucleons of nucleus lead both to the change of composition and number of the particles and to the deformation of their momentum spectra. It is expected that one may distinguish the "c" and "y" distributions by the investigation of the hadron-nucleus interaction characteristics.

A. Bialas and M. Gyulassy [11] have suggested to study the nuclear attenuation for the proton and antiproton produced by pions in the projectile fragmentation region. They have operated with an intermediate state h^* which is formed after the primary interaction, $h_i \to h^*$, of the projectile hadron h_i at the point z_{int}. This state has the cross-section σ_{h^*N} of interaction of h^* with intranuclear nucleon N which is considered to be equal to the interaction cross-section σ_{qN} of the quark q with nucleon. At the point z_{form} it turns into the hadron h_f, $h^* \to h_f$. The above mentioned authors have shown that in the ultimate cases

$$\sigma_{h^*N} = \sigma_{h_fN} = \sigma_{h_iN} \quad \text{or} \quad \sigma_{h^*N} = \sigma_{h_fN} = 0,$$

the A-dependence of the inclusive cross-section is independent of the shape of the distribution $D(x,l,L)$. For the last choice of cross section

$$\sigma_{h^*N} = \sigma_{h_fN} = 0,$$

calculations give too weak attenuation. Carring out a comparison with the experimental data $\pi^- A \to p(\bar{p})X$ at 30 GeV/c [16] A. Bialas and M. Gyulassy have indicated to the preferable

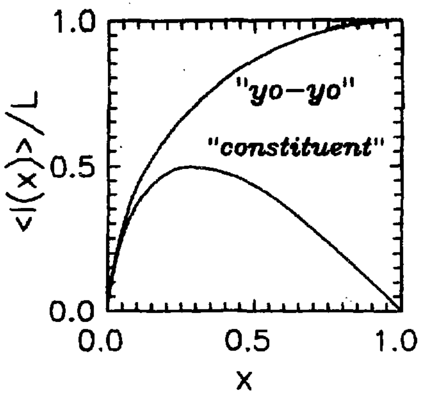

Fig. 1b. The dependence of the average hadron formation length upon x for "yo-yo" and "constituent" definitions [11].

using of the "c"-formation lengths for description of the attenuation of proton and antiproton in the projectile fragmentation region ($x \geq 0.5$). They have considered the approximation of one inelastic collision which leads to the formation of h^*. So in their calculations the string length L is fixed and corresponds to the string length of the same process on hydrogen target.

In the paper [14] of the Frankfurt group the authors have described the same experimental data [16] as those of A. Bialas and M. Gyulassy [11]. They have used the relativistic quantum molecular dynamics (RQMD) model developed by them with σ_{qN} for the intermediate interaction cross section σ_{h^*N}. The results [14] showed that it is insufficient to select a type of formation time only by comparison of the model attenuation with the experimental data. Moreover the calculating results depend not only on the type of the formation time but on the intermediate state cross section and on the form of the fragmentation function for description of quark fragmentation into baryon also. These conclusions lead to some doubts that the choice of the projectile fragmentation region was selected correctly to determine what type of the definition of formation time is true.

On the other hand the realistic string models such as the RQMD or the QGSM are flexible to calculation of other observables and in another kinematical region which can be more sensitive to different definitions of the formation length. We pay the particular attention to the cascade nucleon spectrum which could be more sensitive to the hadron formation time by the force of nonlinear property of their formation (nonlinear effect).

The theoreticians from ITEP [17] have suggested to describe the cascade effects on the nuclei in the framework of the Reggeon theory, where is no notion of the intranuclear cascade in the common sense. They explain the difference between hadron-nucleus and hadron-hadron characteristics by the violation of the cancellation of the planar and nonplanar enhanced diagrams at high energies. But this approach have not been able to describe the sharp peak in the inclusive spectrum of the protons with the laboratory momentum near zero in pA → pX reaction. In the nuclear cascade models this peak is interpreted to be caused mainly by the recoil nucleons formed in the subsequent hadron-nucleon interactions.

Using the Monte Carlo simulation of hadron-nucleus interactions and quark-gluon string model for hadron-hadron collisions [9,10] we have made calculations and analyzed various inclusive and semi-inclusive spectra of protons, mesons and meson resonances for the π^-A-interactions at 21 Gev/c. Unlike [11] we investigated the proton spectra in the target fragmentation region ($x_F \cong -1$) where they have the maximum. As K.Werner and P.Koch noticed [18] the proton momentum spectrum is particular sensitive to the including in the model the rescattering effects (subsequent interactions) .The comparison with the results obtained in [11,14] for the projectile fragmentation region ($x_F > 0.5$) will be done later.

The value of incident momentum and the characteristics under study, used in our calculations, were chosen according to the conditions of the planned experiment *E-852* at the Brookhaven National Laboratory [19]. Particularly, in [20], we have studied the possibility to measure meson resonances in this experiment on the nuclear targets.

The Quark gluon string model

We shall use the Monte-Carlo version of QGSM [9,10] which allows us to investigate the production of different particles including resonances in various kinematical regions. The model describes adequately the data on multiple production in hadron-hadron interactions and gives a possibility to describe the correct space-time picture of particle production using the given definition of hadron formation time. We don't change any parameter of this model, considering it reliably based on the numerous data on hadron-nucleon interaction (see [9,10] and references therein).

According to our approach any hadron, not only the projectile, produces strings in inelastic interaction with the target nucleon, or another hadron. The string length L

$= M_s/2\varkappa$ depends upon its mass M_s and the string tension $\varkappa$. The string mass is not fixed, being determined by longitudinal and transverse momenta of valence quarks on the ends of a string, which are simulated independently for a given hadron momenta at the instant of collision [9]. Thus, the string size L varies from the maximum value, determined by the momentum of a projectile hadron (as in the case of interaction on the hydrogen target), down to the minimum value, determined by mass of the pion. Note that the production of a resonance, for example ρ-meson, requires a greater mass M_s and, accordingly, greater length of the string compared to the pion production.

The strings appear instantly and then decay [9]. Hadrons are produced at the points z^c_{form} (or z^y_{form}). All coordinates z_{form} satisfy the condition $|z_{form} - z_{int}| < L\gamma$, where γ is the string Lorentz factor. It is clear that in the ultimate cases $l\gamma \ll R$ and $L\gamma \gg R$ where R is the nuclear radius, it is impossible to observe any difference between the shapes of the distributions $D_c(x,l,L)$ and $D_y(x,l,L)$. In the first case hadrons in both the versions "y" and "c" are produced inside the nucleus with small formation length and have the same destiny. In the second case they are produced mostly outside the nucleus and undergo no subsequent interactions. The situation is complicated also in the case of $L\gamma \approx R$, since our calculations show a substantial contribution of the processes with $|z_{form} - z_{int}| \ll R$ for both versions.

The strings can live long time and interact with nuclear matter, producing hadrons and other strings. We do not consider string interaction directly. Instead of it strings decay immediately and we know in any moment the space-time coordinates of produced hadrons. Further we will consider such hadrons as "non-formed" hadrons. To satisfy the valon model assumption [11] for "non-formed" hadronic states, which do not contain the valence quarks q_v from the collider particles we put $\sigma_{h^*N} = 0$. The states including valence quarks interact with nucleons of the nucleus with a small cross section equal to the one for the valence quark-nucleon interaction, $\sigma_{h^*N} = \sigma_{q_vN}$, until the formation time is over.

After the formation time has elapsed, (i.e. starting from the point with the coordinate z_{form}) all the "non-formed" hadrons have the cross sections equal to $\sigma_{h_f N}$. Subsequent interactions of the produced hadrons with nucleons and between the hadrons themselves form an intranuclear cascade. The number of subsequent interactions depends upon the free path of a hadron in the nuclear matter $\Lambda_h = 1/\sigma_{h_f N}\,\rho_A$, where ρ_A is the nuclear density. Its value for nucleons $\Lambda_p \approx 1\ fm$ is approximately half that for mesons. This value is to be compared with the radii of nuclei under consideration $R_{Ar} \cong 4\ fm$ and $R_{Xe} \cong 6\ fm$.

Model predictions

Fig.2 shows the distribution of hadron formation coordinate z_{form}, $d^2N/dx_F dz_{form}$, where $x_F = p_L^*/p_{L,max}^*$ is the Feynman variable in the c.m. system of the incident particle - nucleon at rest(CMS). The point $z_{form} = 0$ corresponds to the center of the target-nucleus. The comparison between Fig.2a and 2b shows that on the hydrogen target our distributions agree qualitatively with the distributions of A.Bialas and M.Gyulassy [11]. For the variants "c" and "y" the distributions of z_{form} have quite different shapes (Fig.2b) (the distribution for "c"-version has a peak in the region with the nuclear size) therefore one can expected some differences in the measurable characteristics on the hydrogen and nuclear targets.

However, our calculations for nuclei (see Fig.2c for Ar) show that this is not the case. The z_{form}-distributions do not differ noticeably for the variants with "c" and "y" formation lengths. This is connected with the averaging over the coordinates $\vec{r}_{int}$, and with the substantial contribution of events with the small length ($L_Y < R$) of strings produced in the intranuclear cascade. The events with large x_F, which reveal different shapes of z_{form}-distribution in "c" and "y" representations (Fig.2d) on the nuclear target similarly to that on hydrogen target, give a small contribution in the distribution integrated over x_F. The difference in the shape of z-distributions does not effect the measurable characteristics because there are a few number

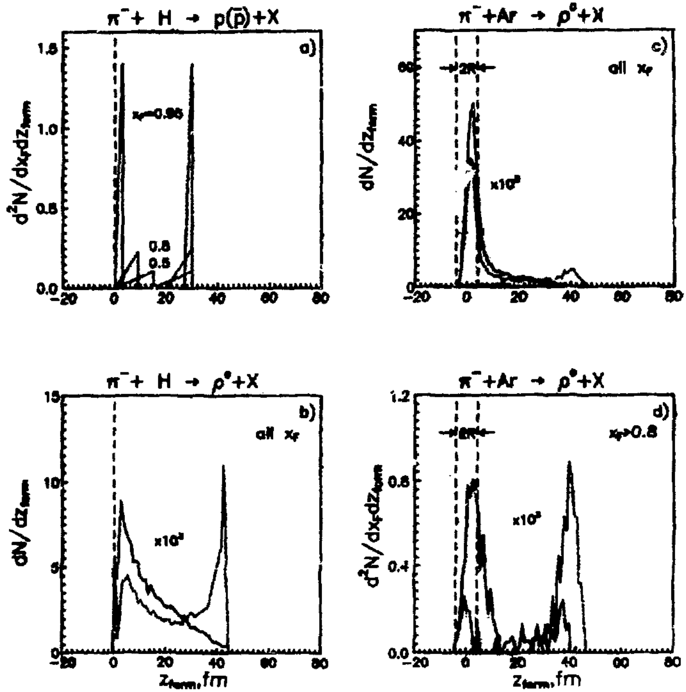

Fig. 2. Distribution of hadron formation coordinates z_{form} for "constituent" (solid curve) and "yo-yo" (dashed line) variants : a)the model from /11/ for the processes $\pi^- A \to p(\bar{p})X$ at 30 GeV/c, b)-d) our calculations for the process $\pi^- A \to \rho^0 X$ at 21 GeV/c.

of subsequent interactions for the fast hadrons formed mostly out the nuclei. It should be noticed that for the integral over all x_F, the ρ^0-mesons are mostly produced in the downstream region $0<z<R$ of the nucleus (fig.2c).

The inclusive spectra of mesons $EdN/dx_F(x_F)$ for the variants "c" and "y" have actually no differences in shape in the interval $x_F>-1$ for π^- and ρ^0 (fig.3). The mean multiplicity of mesons for the variant "c" is ≈10% larger. The analogous results were also obtained by us for the Xe nucleus and for other light mesons.

Fig. 4 shows the inclusive and semi inclusive (i.e. the spectra of protons which coincide with a resonance) proton spectra for two nuclei Ar and Xe in the reactions $\pi^-A\to pX$ and $\pi^-A\to(p+res)X$ respectively. The longitudinal momentum of the protons in the laboratory system (LS)at $x_F=-1$ equals to zero. The values $x_F<-1$ correspond to the protons in the backward hemisphere in the LS (the left slope of the spectrum) and the values $x_F>-1$ - to the forward protons (the right slope of the spectrum). The parameter of the approximating exponent $\exp(-\delta x_F^p)$ in the right part of the proton distribution $E^p dN/dx_F^p(x_F^p)$ is the same for both definitions of the formation length (Fig. 4a.b). It is greater for the constituent formation length in the left part of spectrum (see tab.1); and the difference between the slope parameters increases from Ar to Xe.

The dependence of the slope parameter (or, generally, the different shape of spectra) on the choice of the formation time definition could result from the following reasons. The hadrons born in the string decay undergo the secondary interactions with the nucleons inside nucleus. The recoil nucleons, generated through the different mechanisms of hadron-nucleon interactions in the nucleus, get some momentum. In our calculations they move in the backward hemisphere in LS with the momenta up to 800 MeV, corresponding to $x_F^p=-2.3$ in the CMS of the projectile pion- target nucleon collision.

The number of secondary interactions for "c" variant is greater than for "y" one due to the greater number of

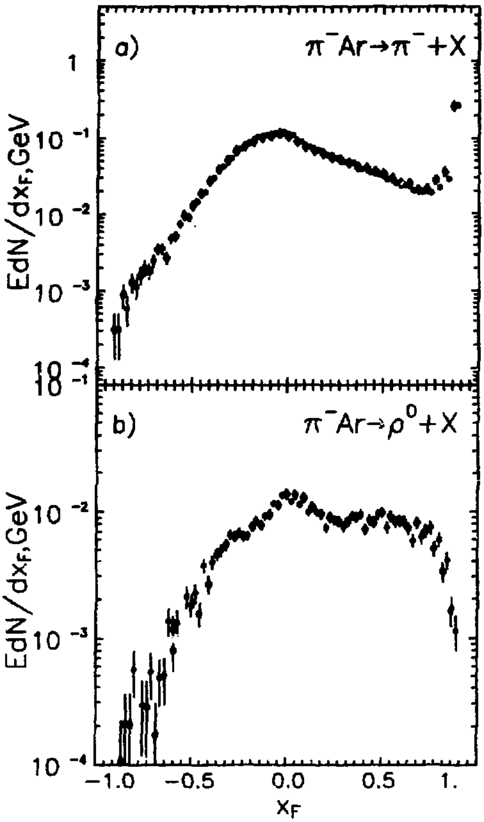

Fig. 3. Inclusive spectra for π^- and ρ^0-meson production in π^-A-interactions at 21 GeV/c in QGSM. The black circles - "constituent", the open rhombs- "yo-yo" variant of hadron formation time. Errors are caused by the number of simulating events.

hadrons produced in the nucleus. It leads to the greater number of the protons in the range of x_F^p=(-1.3 ÷ -0.8) corresponding to the small proton momentum (k^p< 200 MeV/c in the LS). In the region x_F^p < -1.5 the situation is just opposite, causing difference in the slope values of the spectrum in "c" and "y" variants (fig.4a,b). Note that the evaporating nucleons contribute in the momentum region k^p< 200 MeV/c. Our model doesn't take into account the evaporating process so we can't make any prediction in this region.

The subsequent interactions of forward hadrons occur after the point z_{form}. As one can see in fig.2c the distribution over z_{form} peaks in the downstream part of the nucleus 0<z_{form}<R. It means that the recoil nucleons, produced in secondary interactions and flying backward, would traverse a thicker layer of nuclear matter than that flying forward. This circumstance is likely to entail the apparent difference between the proton spectra in the backward hemisphere for "c" and "y" variants. It is still unclear why the proton spectrum in the backward hemisphere for "c" variant is steeper than that for "y" variant, and what is the connection of this effect with the subsequent interactions of produced hadrons or recoil nucleons.

The change of the slope at the left part becomes stronger in the semi-inclusive spectrum of protons from the reaction π^-A->(p+res)X (fig.4c-f) where the resonance (res = ρ,ω) is registrated simultaneously with the proton. The values of the slope are given in table 1. For the ρ and ω these values are the same within the errors. The slope increases from the Ar to Xe since the number of subsequent interactions increases with R. A more significant change of the slope, as we go over from the "y" to "c" formation lengths for the semi-inclusive cross section, is connected with the selection of events: when we registrate the resonance we select the events known to have, on the average, a large string length L. In the events with larger L the differences in shape of the formation length distributions are more pronounced.

The inclusive proton spectra for the reaction π^-A->pX contain a larger contribution of events with

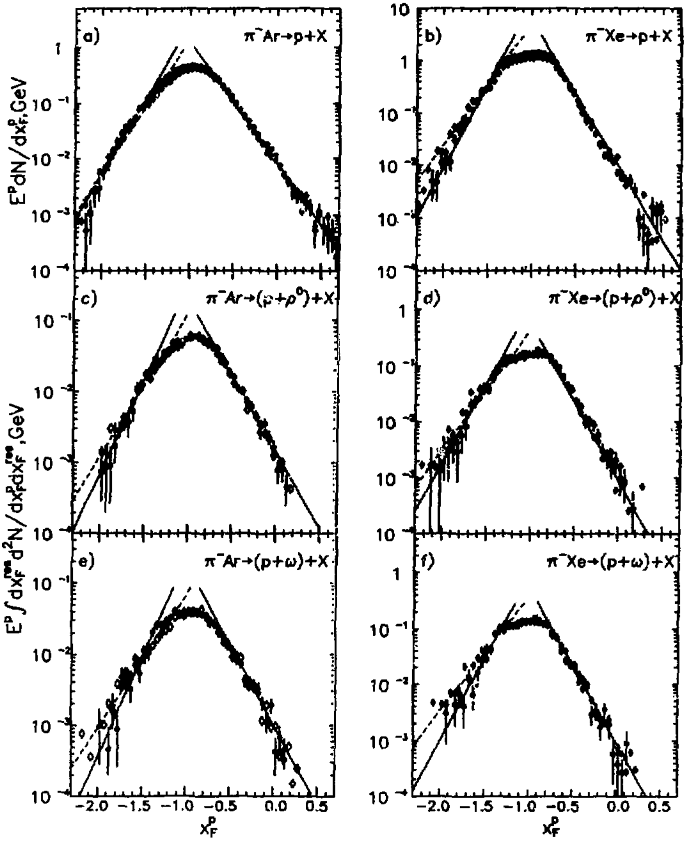

Fig. 4. Momentum spectra of protons in $\pi^-A \to pX$ and $\pi^-A \to (p+res)X$-interactions at 21 GeV/c calculated in QGSM for "constituent" (black circles and solid lines as approximation) and "yo-yo" variant of the formation time (open rombs and dashed line respectively).

Table 1. The slope parameters δ for left ("L") and right ("R") parts of the inclusive EdN/dx_F (1) and semiinclusive $E\int dx_F^{res} d^2N/dx_F^p dx_F^{res}$ proton spectra (2),(3) approximated by an exponent $\propto \exp(\pm\delta x_F^p)$.

		Ar "L"	Ar "R"	Xe "L"	Xe "R"
π A→pX (1)	"y"	5.5±0.2	5.1±.1	5.3±0.1	5.8±.1
	"c"	6.2±0.2		7.3±0.1	
π A→(p+ρ^0)X (2)	"y"	4.6±0.3	4.9±.1	5.0±0.4	6.4±.2
	"c"	5.1±0.5		6.5±0.5	
π A→(p+ω)X (3)	"y"	4.3±0.4	5.2±.2	4.7±0.5	6.4±.2
	"c"	6.4±0.8		6.8±0.8	

pions in the final state which appear predominantly in the breaks of short strings. Therefore the shapes of inclusive spectra for the variants "c" and "y" differ to lesser extent than those of semi inclusive spectra. The difference between the inclusive cross sections for these two variants is also smoothing out due to large admixture of mesons from resonance decays.

Summary

Thus, analyzing the calculations of the different hadron spectra obtained in π^-- A interactions at 21 GeV/c in Monte-Carlo version of QGS model, we could make the following conclusions:

- We have obtained the absence of noticeable differences in the inclusive characteristics for mesons and meson resonances in the case of the versions with "y" and "c" definitions of the formation time for x_F>-1.
- The spectrum of the proton longitudinal momenta, taken in coincidence with the produced resonances, is the most sensitive to the hadron formation time. The slope of the "backward-going" proton spectrum for "c"-definition of the formation time is steeper than for "y" one. This is connected with the position of the maximum in the distribution of the number of hadrons formed inside the nucleus in its downstream region and with the subsequent interactions of both the produced hadrons and the recoil nucleons with the intranuclear nucleons in the process of nuclear cascade development.

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