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HOW ARE THE PROTON MULTIPLICITY DISTRIBUTION OF HIGH ENERGY HADRON-NUCLEUS COLLISIONS AND THE TARGET-NUCLEUS GEOMETRY INTERRELATED?

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1. INTRODUCTION

The opinion exists for a long time that the results of the study of inelastic hadron-nucleus collisions at high energies can serve as a test of models for the hadron-nucleon interaction and may provide such information on the strong interaction of particles which cannot be obtained by investigating hadron-nucleon collisions alone. However, it is clear that before many hadron-nucleon reactions can be analysed on this way an understanding of the hadron-nucleus collision mechanism must be achieved.

But, we meet nowadays with difficulties in attempts to apply any of various existing models of high energy hadron-nucleus collision for simple and accurate quantitative and even the qualitative explanation of existing experimental data. Even such fundamental characteristic as the proton multiplicity distribution of these collisions does not have simple and precise quantitative description. We are sure, in order to reveal true picture of the high energy hadron-nucleus collision process, we must just begin with the precise and physically meaningful description of the distribution of the hadron-nucleus collision events versus the nucleon emission intensity, in particular - versus the usually observed proton multiplicities, and with the elucidation of the physical meaning of this distribution. When it will be done, other various characteristics of the nucleon emission can be explained and the multiparticle creation mechanism in high energy hadron-nucleus collisions might be elucidated. Our belief arises from the discovery of such high energy hadron-nucleus collision events in which the nucleon emission goes on without multiparticle creation act /1/. The intensively emitted nucleons are of kinetic energies from nearly 20 to nearly 400 MeV, as we can conclude from the energy spectra of the observed protons.

For that reason we started some years ago from the studies of the proton emission process in high energy hadron-nucleus collisions, using the pictures from the 180 litre xenon bubble chamber exposed to 3.5 GeV/c negative pion beam /1/. By investigating this process during last few months a great deal of our attention has been given to the collision events in which the projectile causes the emission of nucleons only, without multiparticle creation; the events of the pion-nucleus

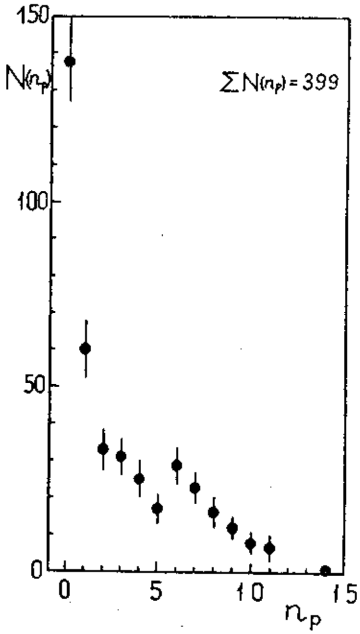


Fig.1. Distribution of fast proton multiplicities in 339 pion-xenon nucleus collision events without multiparticle creation. $N(n_p)$ the numbers of events with the proton multiplicities n_p.

collisions without any secondary pion and those with only one secondary pion and any number of emitted protons have been attributed to this type of cases in our experiments /2/. As a result, it was found that the proton multiplicity distributions of such events are of strange shapes: a/ The peak is observed in the proton multiplicity distribution of the pion-xenon nucleus collision events not accompanied by any secondary pion /2/, at the proton number $n_p = 8$; b/ The proton multiplicity distribution of both the types of events, with single one and without any secondary pion, is evidently inmonotonous /2/ - irregularity is seen at proton number $n_p = 6$, fig.1.

In spite of the fact that these experimental results are of small statistical significance at yet, we can try to use them as an indication in attempting to form some hypothesis which could help to understand the nucleon emission process. We have noticed of the fact that the number of protons lying in the neighbourhood of the xenon target-nucleus diameter is 8, just what is the value of the proton multiplicity $n_p = 8$ at which the peak is located in the distribution of the events without any secondary pion /3/.

Therefore, in order to explain the existence of the events in which intensive emission of nucleons goes on without the multiparticle creation and to derive a formula for the proton multiplicity distribution in them, the working hypothesis has been suggested /3/. We rewrite it here in a little modified form: high energy hadron traversing the nuclear matter causes monotonously the emission of fast nucleons along its path; the number of ejected nucleons equals the number of nucleons met in the neighbourhood to the path of this hadron; in particular, the number of the emitted protons equals the number of protons met. Accepting this hypothesis and using the parameters describing the target-nucleus [4] - the radius R and the radial nucleon density distribution $\rho(r)$, the simple explanation of the proton multiplicity distribution in both the types of events without multiparticle creation has been achieved [3] and the approximate expression describing the proton multiplicity distribution of the total sample of pion-xenon nucleus collision events has been derived [5].

It shall be obvious, from what has been said above, to expect that general formula describing precisely the nucleon multiplicity distribution of all hadron-nucleus collision events might be derived on the basis of our hypothesis and the target-nucleus geometry; we define the geometry of the target-nucleus by the nuclear radius R and by the radial nucleon density distribution $\rho(r)$ in it.

The aim of this paper is to present the derivation of such formula and, doing it, to elucidate how the target-nucleus geometry and the nucleon emission intensity are interrelated, and to show how the nucleon emission in hadron-nucleus collisions is going on.

2. DERIVATION OF THE FORMULA FOR THE PROTON MULTIPLICITY DISTRIBUTION OF HADRON-NUCLEUS COLLISION EVENTS

Let us consider the hadrons falling on identical spherical target-nuclei of the radii R and the radial nucleon density distribution $\rho(r)$; let the probability they to collide with nuclei at any point on the nuclear sphere surface to be constant and the impact parameter being always $d \le R$. Let the ratio between the neutron number A-Z and the proton number Z to be constant inside the target-nucleus, being $\frac{A-Z}{Z}$; it is not far from the existing experimental data [4,6].

As a result of the collisions we observe, in the bubble chamber for example, large variety of pictures of these collisions: the events in which the projectile hadrons are deflected through various angles θ_h , with accompaniment or not by the emitted nucleons [1,2] ; the cases in which many various particles are ejected - pions, kaons, hyperons, nucleons. But what happens there, inside the target-nucleus, we do not know exactly at yet; we may put forward some hypotheses only, as it currently is practiced.

Now we shall do it here too, in order to derive the formula which has to describe accurately the observed proton multiplicity distribution of the hadron-nucleus collision events. But, our assumptions will follow immediately from the experimental data which we have received in experimental investigations of the proton emission process. We accept, namely, that the projectile hadrons may undergo following processes in passing through atomic nuclei: a/ They undergo monotonously the deflection through relatively small deflection angles θ_h ; b/ Sometimes they undergo the deflection through relatively large angle, in such cases the recoil nucleons appear of kinetic energies large enough they to be able to cause monotonous nucleon emission in ones turn; c/ Sometimes the projectiles undergo such collision with one of the nucleons inside the target-nucleus which leads to the multiparticle creation act; d/ The projectile hadrons, the fast recoil nucleons, and the secondaries which appear in the case of the multiparticle creation act cause any time the monotonous nucleon emission in traversing the nuclear matter, according to our working hypothesis.

We mast specify in more detail each of these processes now. We have observed the hadron-nucleus collision events in which the projectile hadron traverses the target-nucleus causing the emission of nucleons, without multiparticle creation, and goes out being deflected through some angle θ_h from its initial straight line course. In most of these cases the deflection angles are smaller than nearly 20 degrees [2]. Many events exist in which larger angles are observed, however. In such class of events enlarged proton emission is evidently seen [2]. The deflection that the projectile hadron undergoes in traversing nuclear matter of finite thickness may be caused either by a single collision, or by many subsequent collisions. It can be proved that large deflections are more likely to occur in single collisions, while small ones are generally caused by many collisions. The result of a single collision is referred to as a single scattering; the result of a large number of collisions, as multiple scattering; the result of a small number of collisions, as plural scattering. We think the reason for the existence of the events in which small deflections of incident hadrons are observed to be the multiple subsequent collisions resulting deflections through very small angles; the reason for the existence of the events in which large deflections are observed to be such that single collisions inside the target-nuclei occur. In such single collisions the recoil nucleons may appear of energies large enough they could cause the monotonous emission of nucleons as well in traversing nuclear matter; we think it to be the cause for the appearance of the enlarged nucleon emission intensity in the hadron-nucleus collision events without multiparticle creation act in which the projectile hadrons undergo the deflections through large angles. As concerns the events in which the multiparticle creation acts take place, we have an argumentation [5] to be able to assume that following scheme to be adequate: in high energy hadron-nucleus collisions the particle creation process goes on by intermediate states decaying into obderved particles after having left the target-nuclei. We are able to apply such assumption in the light of our experimental data [1] too, in confrontation with the working hypothesis: the average number $\bar{n}_p$ of protons emitted in pion-xenon nucleus collisions at 3.5 GeV/c momentum does not depend on the number of the pions produced.

Such scheme we use later as the basis for the derivation of the expression for the proton multiplicity distribution. We do not intend to consider many various possible behaviours of the intermediate states inside the target-nucleus and to take into account various existing models of the multiparticle creation process in hadron-nucleus collisions [7-12]. We restrict here our discussion to the case when the intermediate state is created which moves along the incident hadron course in the target-nucleus and it behaves itself inside the parent nucleus as any hadron does. We have considered other various cases too, but the above-mentioned one leads only to the results being in agreement with the experimental data.

On the basis of the working hypothesis, to defined path length λ of the hadron inside the target-nucleus there corresponds one defined number of nucleons met along it; in particular, to a given length λ defined number of protons corresponds. If the fast recoil nucleons do not appear and only pure monotonous nucleon emission occurs,and the projectile hadron undergoes the deflection through small angle θ_h, the number n_p of protons emitted from the target-nucleus in traversing it by high energy hadron at the distance d from the center of the nucleus is equal to:

$$n_p = \pi \cdot D_0^2 \cdot \bar{\rho} \cdot \frac{Z}{A} \cdot \lambda = \pi \cdot D_0^2 \cdot 2\sqrt{R^2 - d^2(n)} \cdot \bar{\rho} \cdot \frac{Z}{A}, \qquad (1)$$

where D_0 denotes the nucleon diameter [4] which we accept later to be the length unit; $\bar{\rho}$ denotes the average nucleon density along the hadron path λ. But, if the single scattering takes place, the number of emitted protons shall be enlarged, being $n_p' > n_p$. Suppose the hadron undergoes only one single scattering by a nucleon inside the target-nucleus, then the number of protons emitted is expressed by:

$$n_p' = n_p + \pi \cdot D_0^2 \cdot \frac{Z}{A} \cdot \lambda' \cdot \bar{\rho}' = \pi \cdot D_0^2 \cdot \frac{Z}{A} (\lambda \cdot \bar{\rho} + \lambda' \cdot \bar{\rho}'), \qquad (2)$$

where λ' denotes the path length of the recoil nucleon and $\bar{\rho}'$ is the average nucleon density along this path. This single scattering may occur at any point on the λ inside the target-nucleus, however, and the recoil nucleon may be ejected in various directions, then, in some number of hadron-nucleus collisions, different numbers n_p' of protons may correspond to defined impact parameter d .

However, it must be emphasized that the observed nucleon emission accompanying these three types of the projectile hadron scattering should be considered not as a simple pure outknocking process [13] . But, we will see later that the possible nucleon ejection mechanism does not influence the derived distribution. Therefore, we do not discuss this problem here now.

We start now the derivation of the formula for the proton multiplicity distribution of the hadron-nucleus collision events. Let us consider firstly the idealized case of the collision process: let the projectile hadron undergoes the multiple deflection only in traversing the target-nucleus. Then, only monotonous nucleon emission accompanies its passage along almost straight line course. We may write, on the basis of our working hypothesis, for the nucleon multiplicity distribution of such collision events:

$$W_0(n) = \frac{2\pi}{R^2} \int_{\bar{d}(n)-\Delta_1}^{\bar{d}(n)+\Delta_2} \ell \, d\ell = \frac{\Delta_2^2 - \Delta_1^2}{R^2} \cdot \pi + \frac{2\pi}{R^2} [\Delta_1 + \Delta_2] \, \bar{d}(n), \qquad (3)$$

where $\bar{d}(n)$ denotes the "average" impact parameter lying within $[(\bar{d}(n)+\Delta_2) - (d(n) - \Delta_1)]$ interval; $\sum_i \{ [\bar{d}(n)_i + \Delta_{2i}] - [\bar{d}(n)_i - \Delta_{1i}] \} = \sum_i [\Delta_{1i} + \Delta_{2i}] = R$. To the parameter $\bar{d}(n)$ there corresponds definite hadron path inside the target-nucleus, $\bar{\lambda}(n) = 2\sqrt{R^2 - \bar{d}(n)^2}$ on which n nucleons are met, according to the formula (1).

Analysing the values $\Delta_1 + \Delta_2$ for various nuclei, from the light, as ^{12}C, to heavy ones, as ^{235}U, we see that we can accept $\Delta_1 \doteq \Delta_2 \doteq \Delta$ = constant for the s - region[4], and we can rewrite the formula (3):

$$W_0(n) \doteq \kappa \, \bar{d}(n) = \bar{d}(n), \tag{3'}$$

where κ = constant which can be put to be equal to 1. We omit here the argumentation that this expression can be applied, too, for all the impact parameters $\bar{d}(n)$.

However, pure monotonous emission goes on only in some part of all collision events without multiparticle creation. In the rest part of these events the single scattering of the incident hadron by nucleon inside target-nucleus takes place, and the enlarged nucleon emission occurs. Such single scattering goes on with the intensity being proportional to the length $\bar{\lambda}(n)$; μ_s being the coefficient of the proportionality. Then, we can write the expression for the nucleon multiplicity distribution $W_1(n)$ of the collision events without multiparticle creation acts in which the hadrons cause the pure monotonous nucleon emission only:

$$W_1(n) = W_0(n) e^{-\mu_s \cdot \bar{\lambda}(n) \cdot \bar{\rho}(n)} . \tag{4}$$

The formula (4) has to describe accurately the nucleon multiplicity distribution of such observed hadron-nucleus collision events in which the projectile hadrons are deflected through relatively small angles. The meaning of the word "small" should be determined from the experimental data; as we can see[2], these angles should be smaller than the maximum deflection angle θ_{max} at which the inmonotony in proton multiplicity distribution does not appear. The formula (4) describes the proton multiplicity distribution as well, because the ratio $\frac{A-Z}{Z}$ can be accepted to be constant inside the atomic nuclei. Then, we will denote n_p simply by n, for a convenience, and consider the proton multiplicity only later on.

Let us include now into the formula the events with single scattering, and estimate their contribution to the proton multiplicity distribution at various proton numbers n. The number of such events, for the values $n_p \equiv n$, is expressed by $W_0(n)[1 - e^{-\mu_s \cdot \bar{\lambda}(n) \cdot \bar{\rho}(n)}]$. We should now derive a new expression for the proton multiplicity distribution $W(n)$ accounting these events. For this reason we divide the path length $\bar{\lambda}(n)$ into some number of parts $\Delta\lambda(n)$ being approximately of such a length on which nearly one proton can be met:

$$\Delta\lambda(n) = \frac{\bar{\lambda}(n)}{n}. \quad (5)$$

Then, we can write the formula $W(n)$ for the proton multiplicity distribution of such events in which multiple collisions and unifold single hadron-nucleon collisions take place in target-nucleus:

$$W(n) = W_1(n) + W_2(n), \quad (6)$$

where $W_2(n)$ are the terms accounting the enlarged proton emission in the events with single scattering.

Explicitly, we write:

$$W(0) = W_1(0),$$

$$W(1) = W_1(1) + 0,$$

$$W(2) = W_1(2) + k\{[2-1]\to 2\}\cdot W_0(1)\cdot\{1-e^{-\mu_s\cdot\bar{\lambda}(2-1)\cdot\bar{\rho}(2-1)}\}\times$$
$$\times\{1-e^{-\mu_s\cdot[2-1-1]\cdot\Delta\lambda(2-1)\cdot\bar{\rho}(2-1)}\}e^{-\mu_s\cdot\Delta\lambda(2-1)\cdot\bar{\rho}(2-1)},$$

$$W(3) = W_1(3) + k\{[3-1]\to 3\}\cdot W_0(2)\cdot\{1-e^{-\mu_s\cdot\bar{\lambda}(3-1)\cdot\bar{\rho}(3-1)}\}\times$$
$$\times\{1-e^{-\mu_s\cdot[3-1-1]\cdot\Delta\lambda(3-1)\cdot\bar{\rho}(3-1)}\}e^{-\mu_s\cdot\Delta\lambda(3-1)\cdot\bar{\rho}(3-1)},$$

....

$$W(5) = W_1(5) + k\{[5-1]\to 5\}\cdot W_0(4)\cdot\{1-e^{-\mu_s\cdot\bar{\lambda}(5-1)\cdot\bar{\rho}(5-1)}\}\times$$
$$\times\{1-e^{-\mu_s\cdot[5-1-1]\cdot\Delta\lambda(5-1)\cdot\bar{\rho}(5-1)}\}e^{-\mu_s\cdot\Delta\lambda(5-1)\cdot\bar{\rho}(5-1)}+$$
$$+\ k\{[5-2]\to 5\}\cdot W_0(3)\cdot\{1-e^{-\mu_s\cdot\bar{\lambda}(5-2)\cdot\bar{\rho}(5-2)}\}\times$$
$$\times\{1-e^{-\mu_s[5-2-2]\cdot\Delta\lambda(5-2)\cdot\bar{\rho}(5-2)}\}\cdot e^{-\mu_s\cdot\Delta\lambda(5-2)\cdot\bar{\rho}(5-2)},$$

....

and, in general:

$$W(n) = W_1(n) + \sum_{i=1}^{i=E(\frac{n-1}{2})} k\{[n-i]\to n\}\cdot W_0(n-i)\{1-e^{-\mu_s\cdot\bar{\lambda}(n-i)\cdot\bar{\rho}(n-i)}\}\times$$

$$\times\{1-e^{-\mu_s\cdot[n-2i]\cdot\Delta\lambda(n-i)\bar{\rho}(n-i)}\}e^{-\mu_s\cdot i\cdot\Delta\lambda(n-i)\cdot\bar{\rho}(n-i)} + O(n), \quad (7)$$

where $i = 1, 2, 3, \ldots, E(\frac{n-1}{2})$; $n = 0, 1, 2, 3, \ldots, 2n_D - 1$ and n_D denotes the number of protons lying in the neighbourhood to the target-nucleus diameter; $k\{[n-i]\rightarrow n\}$ denotes the coefficient accounting the probability that the recoil nucleon traverses appropriate thickness of nuclear matter; $O(n)$ denotes a small term accounting the inaccuracies caused by simplifications involved in deriving the formula.

In the light of our working hypothesis and in the frames of our pictures of the hadron-nucleus collision process and of the multiparticle creation act, the formula (7) should reproduce the proton multiplicity distribution of the total sample of hadron-nucleus collisions too: the class of events without multiparticle creation and the class of those with multiparticle creation together. This formula describes each of those classes of events separately as well but, in any case suitable attenuation coefficient μ_s must be estimated, on the basis of appropriate experimental data.

Usually we record and select, with the efficiency close to 100%, the events in which multiparticle creation acts take place. But, we do not select, with such large efficiency, the events in which multiparticle creation process does not accompany the hadron-nucleus collisions; we lose then the events in which the projectile hadrons are deflected through the angles θ_h smaller than some $\theta_{h\,min}$; the scanning and selection criteria of the events designed for the further analysis lead, too, to the losses of other special cases of the collision events with many emitted protons and without multiparticle creation act. Then, the formula which should be describeing precisely the experimental data must be the composition of two terms:

$$W_e(n) = \frac{k_1}{N} W_{e1}(n) + \frac{k_1}{N} W_{e2}(n). \quad (8)$$

where $W_{e1}(n)$ is the proton multiplicity distribution of the collision events with multiparticle creation acts, amounting k_1 events; $W_{e2}(n)$ is the proton multiplicity distribution of the collisions without multiparticle creation acts, amounting k_2 events; N is the total number of events recorded in experiment in both these classes of collisions; the index e indicates that the distribution (8) is comparable with the experimental data.

It should be noted that expression (7) is derived in as - sumption that the projectile hadron or the intermediate state created by it undergo unifold single scattering only in traversing nuclear matter. In fact many quasielastic collisions of the projectile or the intermediate state may occur in accompaniment of the fast recoil nucleons being able to cause monotonous nucleon emission in ones turn. In such case of the plural scattering the expression for the proton multiplicity distribution will be more complicated. We hope, however, that the derived expression (7) gives the predictions which will agree well with now existing experimental data.

3. COMPARISON OF THE FORMULA WITH APPROPRIATE EXPERIMENTAL DATA

A comparison of the formulas (7) and (8) with suitable experimental data is a subject to this section. We use the experimental proton multiplicity distributions received in investigating the pion-xenon nucleus collisions at 3.5 GeV [1,2],

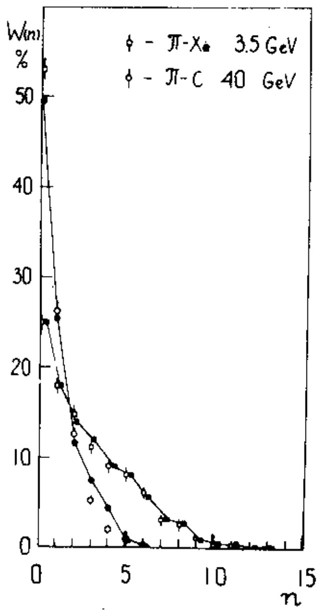
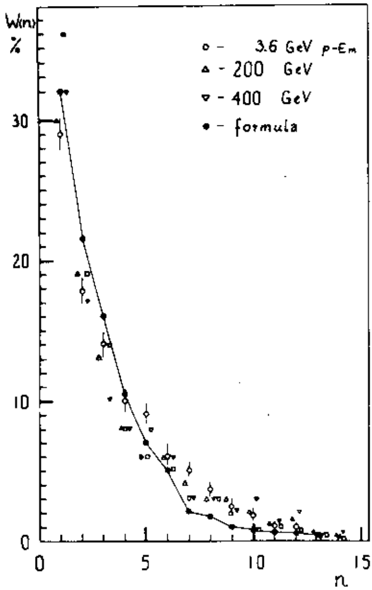


Fig.2. Comparison of the experimental proton multiplicity distributions in pion-xenon [1] and pion-carbon [16] nuclei collisions with the distributions predicted by the formula (7). Black figures and solid curves connecting to them represent the predicted distributions.

the pion-carbon nucleus collisions at 40 GeV [16], and the pion-nucleus and proton-nucleus collisions at 3.5, 200, and 400 GeV registered in photonuclear emulsions[14-17].

The coefficients μ_s were estimated in fitting the experimental numbers of events at $n = 1$ and $n = 2$, $N(1)$ and $N(2)$, the predicted ones $W(1)$ and $W(2)$, correspondingly. The values $\bar{\lambda}(n)$ and $\bar{\rho}(n)$ were estimated using the radii R of the target-nuclei and the Fermi's nucleon radial density distribution $\rho(r)$ in them [4].

Fig.3. Comparison of the proton multiplicity distribution of the hadron-nuclei collision events, prepared for the photonuclear emulsions using formula (7), with the experimental grey track multiplicity distributions in the pion-emulsion and proton-emulsion collisions at various energies /14-17/.



The coefficient $k\{[n-i]\to n\}$ was estimated roughly from the geometrical relations inside target-nucleus. The following percentage of various target-nuclei in photonuclear emulsions has been used: J - 0.30%, Ag - 12.4%, Br - 12.4%, S - - 0.31%, O - 10.75%, N - 4.25%, C - 19.69%, H - 40.13%.

The comparison of the experimental proton multiplicity distributions with the predicted by the formula (7) is shown in fig.2 and fig.3.

4. DISCUSSION

The predicted proton multiplicity distributions agree well with the experimental ones. We may state therefore that the picture of the hadron-nucleus collision process used in our considerations might correspond to the reality, and, in fact, the monotonous nucleon emission takes place along the high energy projectile-hadron path inside nuclear matter.

It should be emphasized that within the frames of our picture the target-nucleus dimensions and the radial nucleon density distribution in it determine completely the proton multiplicity distribution of the hdron-nucleus events. It is remarkable that the target-nucleus geometry manifests its importance in high energy nuclear processes in such clear manner.

The target-nucleus radius and the radial nucleon density distribution $\rho(r)$ play principal role in formula (7). But, the evidence of used nucleon density distribution is well enough in the surface region of the nuclei and establishes with considerable accuracy the maximum density, the thickness of the radial distance at which the density has fallen to half its maximum value. It is less clear in the interior, where the possibility of a slight decrease of the density towards the centre of the nucleus cannot be excluded. Therefore, we might expect some inaccuracies in our predictions by formula (7) at the proton multiplicities corresponding to the interior region of the heavy target-nuclei. We will consider this question in the next paper.

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